Re-evaluating participatory catchment management: Integrating mapping, modelling, and participatory action to deliver more effective risk management

ROLLASON, EDWARD,DAVID

Re-evaluating participatory catchment management: Integrating mapping, modelling, and participatory action to deliver more effective risk management

Edward D Rollason

Recent policy changes, such as the EU Water Framework Directive, have transformed catchment management to consider connected socio-ecological systems at the catchment scale, and integrate concept of public participation. However, there is relatively little research exploring how effective these changes have been in altering existing practices of management. Adopting a transdisciplinary approach, this thesis investigates a range of perspectives to explore existing participatory practices in current catchment management, and understand how we can integrate alternative knowledges and perspectives. The research employs diverse social and physical science methods, including participant led interviews and participatory mapping, numerical flood modelling, and the creation of a participatory competency group.

The research finds that, despite the participatory policy turn, established supra-catchment scale drivers continue to dictate top-down practices of everyday catchment management, excluding local communities from decision-making power. In contrast, participation in managing extreme events is actively encouraged, with the development of community resilience a key objective for management agencies. However, the research findings suggest that a similar lack of meaningful participation in knowledge creation and decision-making restricts resilience building. Based on these findings, the research explores practical ways in which participation and resilience can be embedded in ICM, using the typically expert-led practice of numerical flood modelling to show how existing practices of knowledge creation can be enhanced. The thesis also demonstrates how new practices of knowledge creation, based on social learning, can be used to develop new, more effective ways of communicating flood risk and building local resilience.

The thesis proposes a new framework for the management of connected socio-ecological catchment systems, embedding evolutionary resilience as a practical mechanism by which public participation and the management of everyday and extreme events could be unified to develop more effective and sustainable catchment management and more resilient communities.

[Page left intentionally blank]

Re-evaluating participatory catchment management

Integrating mapping, modelling, and participatory action to deliver more effective risk management

Edward D Rollason

Thesis submitted for the degree of Doctor of Philosophy

Department of Geography

Durham University

2018

[Page left intentionally blank]

Table of contents

List of tables

[Page left intentionally blank]

List of illustrations

Publications and presentations

The following publications have arisen from the research presented in this thesis and make up chapters 2-4:

Rollason E., Bracken, LJ., Hardy R.J & Large A.R.G. (2018c) Evaluating the success of public participation in integrated catchment management. Journal of Environmental Management.

Rollason E, Bracken LJ, Hardy RJ, Large ARG (2018b) The importance of volunteered geographic information for the validation of flood inundation models. Journal of Hydrology 562:267–280. doi: 10.1016/j.jhydrol.2018.05.002

Rollason E, Bracken LJ, Hardy RJ, Large ARG (2018a) Rethinking flood risk communication. Nat Hazards 1–22. doi: 10.1007/s11069-018-3273-4

The research has also been presented at a range of conferences, and the comments on and discussions around these presentations have helped shape the research process and the final thesis outputs.

Rollason E., Bracken, LJ., Hardy R.J & Large A.R.G. 'The importance of volunteered geographic information for the validation of flood inundation models', paper presented to Validation in Flood Risk Modelling: combining scientific, policy and market perspectives Workshop, Milan, 2017

Rollason E., Bracken, LJ., Hardy R.J & Large A.R.G. 'Rethinking flood risk communication', paper presented to 7th International Conference on Flood Management, Leeds, 2017

Rollason E., Bracken, LJ., Hardy R.J & Large A.R.G. 'Using a participatory framework to develop new approaches to flood risk communication', paper presented to the European Geosciences Union Annual General Assembly, Vienna, 2017

Rollason E., Bracken, LJ., Hardy R.J & Large A.R.G. 'Validation of flood inundation models using multi-dimensional data and a novel, mixed methods approach', poster presented at the European Geosciences Union Annual General Assembly, Vienna, 2017

Rollason E., Bracken, LJ., Hardy R.J & Large A.R.G. 'Multi-dimensional perspectives of flood risk: Applying local knowledge to understanding, mapping, and communicating flood dynamics', poster presented at British Society for Geomorphology Annual Meeting, Plymouth, 2016

Declaration of copyright

I confirm that no part of the material presented in this thesis has been previously submitted by me or any other person for a degree in this or any other university. In all cases, where it is relevant, material from the work of others has been acknowledged.

Acknowledgement of funding

This work was supported by the Natural Environments Research Council [grant number NE/L002590/1]

[Page left intentionally blank]

Acknowledgements

The requirement for sole publication of a thesis does not allow me to properly acknowledge the full roles of all of the people who have participated in making this research what it is. However, I would like to extend my deepest gratitude to everyone who participated in or helped with the research in any way.

Specifically I must thank all of those people at Quaking Houses, South Moor and South Stanley, and the members of the Greening the Twizell Partnership who participated in the early research work represented by Chapter 2. In the Tyne Valley I also need to thank Northumberland County Council for their help facilitating the research in the aftermath of Storm Desmond. At Corbridge, the members of the Corbridge Flood Action Group made me welcome and gladly gave their time, even whilst some of them were still not back in their homes following the floods. Chapter 3 would not have happened without you. Particular mention must go to the members of the Corbridge Flood Research Group, without whom none of the work presented in Chapter 4 would have been possible.

In Durham and Newcastle I must thank my supervisors, Professor Louise Bracken, Professor Rich Hardy, and Dr Andy Large for their support and encouragement during my slow and sometimes problematic transition (rehabilitation?) from industry back into academia, and for pushing me to achieve as much as I possible could. Also the support staff who have helped me navigate the unfamiliar environment of the university. I am also grateful to the IAPETUS Doctoral Training Partnership and NERC for providing the funding to undertake the research. The DTP also provided me with a strong friendship group and support network at crucial times. Special thanks must go to Diana, without whom I would never have reached the finish line. Outside of work, the wider community of the geography department (particularly Simon and Callum) has made the last 3 years a thoroughly enjoyable experience.

At home, thanks go to my parents for their encouragement and support in taking the plunge to go back to research, and last, but not least, to my wife Cat; I'm aware the last 3 years have not been an easy process but I couldn't have done them without you.

Finally I must thank Dr Nigel Watson and Professor Glenn MacGregor for the friendly but robust and lively viva discussion that formed the closing act of the PhD process. The discussions and recommended corrections have significantly strengthened sections of the thesis, and have prompted additional thought and discussions for how the research might be developed further.

Chapter 1 Introduction

1.1 Background and motivation

Floods are a major environmental hazard across Europe (Kundzewicz et al., 2017), and over the last two decades, have caused billions of euros worth of damages (Munich Re, 2013), killed over one thousand people (Mokrech et al., 2015) and displaced more than half a million people (European Environment Agency, 2008). Climate change predictions suggest that the likelihood of flooding across Europe will increase in the future as a result of increases in the severity and frequency of extreme rainfall events (Hirabayashi et al., 2013). Socio-economic changes, such as population increase and urban expansion, are also likely to result in increases in flood risk (the combination of flood occurrence and consequence) as more people are exposed to the potential impacts of floods (Reynard et al., 2017). Flooding consequences are far reaching. Floods produce a threat to lives, damage property and possessions, and have wide ranging and long term impacts on individuals and communities. These include increases in morbidity and significant increases in physical disease, as well as mental health issues amongst people affected by flooded, both those evacuated from flood affected areas and those living in at-risk areas (Lamond, 2014; Lamond et al., 2015; Milojevic et al., 2017; Munro et al., 2017; Waite et al., 2017).

Traditionally across Europe flood risk has been addressed through a flood defence policy centred on the construction of hard flood defences (Nye et al., 2011; Tunstall et al., 2004). These defences are intended to prevent flooding from occurring, meaning that individuals and communities living in areas at-risk are not impacted by floods. However, recent major flooding events have highlighted the limitations of the flood defence approach (Klijn et al., 2008); critics have also highlighted how the construction of flood defences encourages construction in flood risk areas, resulting in long term increases in risk necessitating the continued construction and maintenance of flood defences (Collenteur et al., 2015).

In recognition, floods are increasingly being recognised as integral aspects of wider catchment systems, the consequences of which need to be managed, rather than defended against. Integrated Catchment Management (ICM) approaches are increasingly being adopted which look to address environmental systems at the catchment scale (Lerner and Zheng, 2011). ICM adopts an inter-disciplinary philosophy for the management of hydrological catchment systems, with an ethos of participation and participatory governance (Falkenmark et al., 2004). Legislation such as the EU Water Framework Directive 2007 (WFD) and the subsequent EU Floods Directive 2007 (FD) have embedded ICM concepts at the European policy level, and these have cascaded to national level policy through instruments such as the UK Catchment Based Approach (CaBA) (Defra, 2013).

Working together in partnership with management organisations and at-risk individuals and communities, the research looks to develop our understanding of how policy on ICM is interpreted in practice, and how this impacts on public participation in hydrological catchment management. This thesis looks to explore the nature of integrated management, public participation, and resilience in an integrated fashion by adopting a transdisciplinary research approach (Bracken et al., 2015; Frodeman and Pacheco, 2016). Using flood risk as a principle example, due to its historically expert-led, command and control focus (Lane et al., 2011b; Maynard, 2013; Wehn et al., 2015), the research also looks to explore and demonstrate practical mechanisms by which people can be more effectively integrated into existing practices of knowledge creation, and how we can adopt alternative participatory practices to generate new, shared knowledge. Using the main findings from this research, the thesis makes recommendations for how future catchment and flood management might be enhanced, and how we might develop more flood resilient communities in the future.

1.2 Research Approach

The research presented in this thesis straddles the intersection of three principle research areas (Figure 1-1):

1. **The governance of catchment and flood management:**
   Catchment and flood management is governed by a wide range of overlapping legislative drivers. This includes supra-catchment scale legislation such as the EU Water Framework Directive 2000 and the EU Floods Directive (2007). These European-scale pieces of legislation resulted in the comprehensive structural realignment of how the water environment is managed. However, catchment systems are also governed by other areas of legislation at a national scale, for example legislation dictating urban planning policy, or agricultural policies. These different governance drivers are enacted through separate, typically siloed, government departments, management agencies, and third sector bodies which operate at different spatial and temporal scales, and with different objectives. The interaction between different legislative and other drivers at different scales, and the relationships between different management organisations has profound impacts on local practices of management being undertaken at the national, catchment, and local scales. Exploring how different drivers are interpreted, how different groups within the management structure work together, and how this impacts on the practices of management undertaken at the local level can help us understand how and why management is undertaken in different situations.

2. **Catchment and Flood Risk Management practices:**
   Driven by changes in catchment governance and attitudes to participation, practices of catchment management have ostensibly shifted to become more integrated and participatory. However, the complex way in which policy is translated into practice, with interconnected networks of stakeholders and drivers at different scales, means that the extent to which this has occurred

is debated. As one of the principle drivers for catchment management, Flood Risk Management (FRM) represents a key area in which governance, management in practice, and public participation can be explored. Exploring and demonstrating practical opportunities for better using and working together with alternative perspectives and knowledges offers opportunities for enhancing local catchment management of floods and wider catchment systems.

3. **Public participation in environmental decision making:**
   Although EU and local policy in England and Wales specifies why the public should be involved in environmental decision making and management, how this occurs, when, and for whose benefit varies significantly depending on project scale and scope. Understanding the relationships between how governments and management agencies perceive the role of public participation in environmental decision making, and local community perceptions and aspirations of their role helps us understand how we can more effectively bring together alternative perspectives.

The research presented in this thesis occupies and explores the space at the intersection of the three research areas of catchment governance, catchment and flood risk management, and public participation. This 'space' is broadly characterised by the concept of ICM (Figure 1-1), which is the principle focus around which the research is constructed, and through which the findings are framed and interpreted. The next section examines existing research around these themes and the intersections between them.

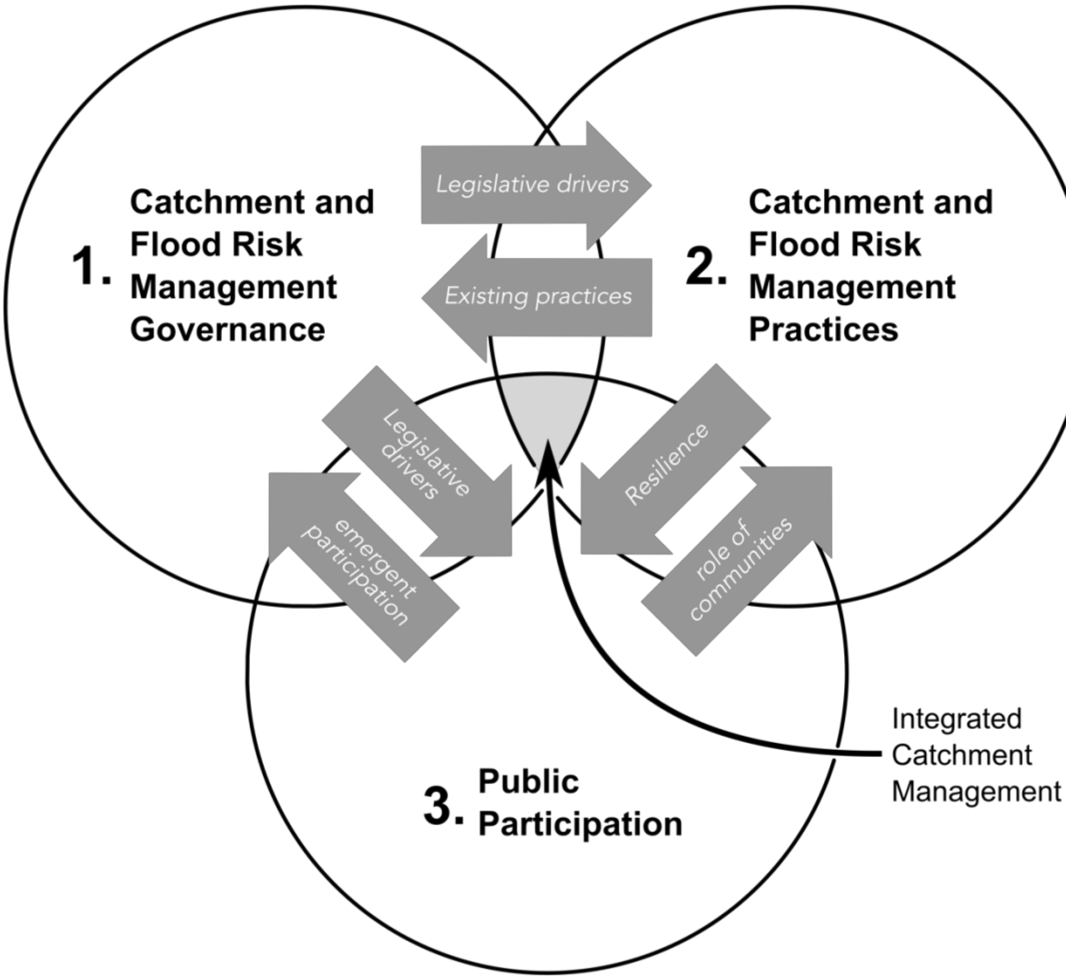


Figure 1-1. The principle areas of research and their intersection.

1.3 Aim and objectives of the research

The aim of this thesis is to investigate a range of perspectives to explore existing participatory practices in current hydrological catchment management, and understand how we can best integrate alternative knowledges and perspectives to better manage catchments and develop more resilient communities in the future.

To meet this aim, the thesis has the following objectives:

1. To explore the nature of public participation in Integrated Catchment Management in practice.
2. To use numerical modelling techniques, alongside participatory research methods, to investigate, using the concept of Flood Risk Management,

how local knowledge and perspectives can be integrated into existing structures of scientific knowledge creation.

3. To use participatory research methods to explore the role of flood risk communications in community resilience building, and work together with at-risk communities in developing new approaches to communicating risk.
4. To make recommendations for how existing approaches to understanding and working together with local perspectives could be improved to enhance future catchment management and develop more resilient communities.

1.4 Fundamental Research

1.4.1 The transition from flood defence to integrated management

In response to the identified limitations of the flood defence approach, FRM has seen a shift in focus towards the acceptance of floods as natural processes and the need to manage their impacts as and when they occur (Defra, 2005; Steinfuhrer et al., 2008; Tunstall et al., 2004). This policy shift is aligned with wider changes in the way in which the water environment more generally is managed, characterised by the ICM approaches to management promoted by the WFD and the subsequent EU Floods Directive. The WFD promotes a catchment based approach to the management of the fresh water environment (Moss, 2004) and, although the WFD is predominantly focused on freshwater pollution, the subsequent EU Floods Directive (European Parliament and the Council, 2007) has extended this approach into flood management (Newig et al., 2014; Nones, 2015), unifying these into a more ICM-oriented approach. ICM approaches to water management consider the hydrological catchment as the natural organising unit for management of the water environment (Hering et al., 2010), with water quality and flood risk considered as integral parts of the connected hydrological system of the catchment, needing to be managed together along with other connected aspects of the catchment system such as land management (Moss, 2004).

1.4.2 Public participation in environmental decision making: the shift from government to governance

The shift from single-issue management approaches to more integrated, ICM approaches also reflects the transition in western states in the 1980s and 1980s from state-led intervention and control to more mixed approaches to management (Jordan et al., 2005; Plüss, 2014). This transition, driven by the election of predominantly neoliberal governments in amongst other places the UK, USA, Australia and New Zealand, is often characterised as a shift from a 'government' to a 'governance' structure of social and political management (Goodwin, 2009). In a government model, central government has principle responsibility for the management of societal and environmental issues, sometimes referred to as rowing the boat' (Peters, 2011; Peters and Pierre, 1998). In contrast, governance models situate central government in a 'steering the boat' role (Peters, 2011), with decision-making powers transferred into a multi-level, multi-scale network of interconnected bodies including non-state actors and, most importantly in this context, individuals and communities (Goodwin, 2009)

This transition be seen in action in England and Wales, where responsibility for flood defence and environmental management, in the 1980s the responsibility of the National Rivers Authority, has been fragmented between Defra and its associated non-departmental public body, the Environment Agency, with overarching 'steering' responsibilities for strategic environmental management, responsibility for fluvial and coastal flood risk management, and a role as environmental regulator (Environment Agency, 2011); Local Authorities, with responsibilities for local flood risk management (Great Britain, 2010); and third sector organisations such as Rivers Trusts, who have taken on significant roles in undertaking freshwater environmental enhancement works (Cook et al., 2012). In parallel, privatised water companies have responsibilities for managing water pollution and flooding from sewer networks, and are overseen by a separate non-ministerial government department, the Water Services Regulation Authority (Ofwat) (Robins et al., 2017).

The shift towards governance has been argued to reflect the underlying neoliberal drivers of individualism and the need to reduce the size of the state (Chandler, 2014; Skelcher, 2000). However, it has also been argued to reflect the increasing importance of complex, inter-disciplinary problems (Ludwig, 2001) requiring the combined actions of multiple stakeholders (Peters, 2011). The focus of ICM on the local characteristics of catchment systems, and the impossibility of developing and implementing generalised solutions (Lerner and Zheng, 2011), can be seen to directly link to this conceptualisation of governance.

Similarly the role of the public, characterised typically as either 'communities' or 'citizens', can be also be seen through this lens. This can be viewed either benevolently, as increasing the power of the local in shaping environmental decision making , or less benevolently, as the simple rolling back of the state and the transfer of responsibility for action onto individuals, without necessary any commensurate transfer of power (Johnson and Priest, 2008; Lee and Abbot, 2003). Regardless of the interpretation, the public dissemination of environmental information, and the promotion of public participation in environmental decision making, have developed as key aspects of ICM policy (Dungumaro and Madulu, 2003; Warner, 2006). These requirements are key components of the EU Aarhus Convention (Lee and Abbot, 2003) and the subsequent WFD and Floods Directive (Newig and Koontz, 2014; Stickler et al., 2012). Ostensibly, this is intended to encourage not just the **consultation** of said-affected publics, which is characteristic of traditional, expert-led approaches to management, but instead the meaningful integration of affected publics into the planning and implementation of catchment management (European Commission and Directorate-General for the Environment, 2003). The degree to which this is the case is debateable (Lee and Abbot, 2003), with ongoing debates regarding the continued dominance of centralised bureaucracy in catchment management approaches (Watson et al., 2009).

1.4.3 Resilience: public participation in managing floods

As well as legislative drivers to increase the role of the public in environmental decision making, accepting floods as a natural part of the water environment means that those living in areas at-risk from floods are increasingly affected by their impacts. The behaviour of at-risk individuals and communities is a key factor in dictating the severity of flood impacts (Brody et al., 2010); the adoption of protective behaviours, such as evacuation prior to floods (Simonovic and Ahmad, 2005) or the installation of flood resistant or resilient technologies in properties can reduce short and long term flooding impacts (Bonfield, 2016). At-risk individuals and communities have therefore become a front line in the management of flood risk (Johnson and Priest, 2008; Mees et al., 2016) and significant policy effort has been devoted to understand how protective or resilient behaviours can be promoted. Chandler (2013) argues:

> "*how the population, or society in general, proactively engages with, and adapts to, uncertainty has been at the heart of recent UK policy discussions on how to empower citizens to be more capable of governing themselves through making better life choices in the face of risk and complexity*" (p. 212)

This changing view reflects a broad 'socialisation' (Nye et al., 2011) of hazard management, and a downwards transfer of management responsibility from traditional, top-down management organisations onto individuals and communities at-risk from hazards. In the context of floods, this socialisation of management has predominantly been interpreted through the development of local level resilience (Thieken and Beurton, 2012; Thieken et al., 2014), a concept embraced by the many elements involved in the management of flood risk; from the rhetoric of policy, through to preparation for flooding, event management and response.

Resilience is a contested concept with a broad range of definitions existing within the literature (Bahadur et al., 2010; Cutter, 2016; Manyena, 2006). Hollin (1973) proposes two major differentiations between resilience definitions, those derived from engineering, and those from ecology (Walker and Cooper, 2011). Engineering resilience is defined as "*as the ability of a system to return to an equilibrium or steady-state after a disturbance*" (Davoudi, 2012, p. 300). Definitions of resilience grounded within engineering thinking are focused on 'bounce-back' (Davoudi et al., 2013) and levels of resilience are dictated by how much resistance a system puts up to a disturbance and how readily is rebounds to its pre-disturbed state. In contrast ecological resilience focuses on the magnitude of a disturbance that a system is capable of absorbing before it is altered into a new state by external forcing; a continuous process of persistence followed by adaption (Adger, 2000; Folke, 2006), often characterised through multi-scale adaptive cycles (Carpenter et al., 2001). Although different, both definitions assume the presence of equilibria or a steady state within systems, whether this is a pre-existing situation to which a system can return (as in engineering resilience) or a new one to which a system can transition (as in ecological resilience) (Davoudi et al., 2013).

These definitions are often combined in operational definitions of resilience and the nuanced meanings debated in academic research become eroded and conflated into straightforward, everyday uses. For example, research undertaken to support the implementation of the EU Floods Directive (Thieken et al., 2014) argues that resilience is a three part process: (i) resistance to a shock or disturbance; (ii) recovery from the disturbance, with the time taken to return to a pre-shock state an indicator of resilience; and (iii) adaptive capacity, or the ability of the system to learn from past shocks and adjust to new conditions. Of these three facets of resilience, (i) and (ii) can both be seen to be drawn from an engineering conceptualisation of resilience, with (iii) incorporating Hollins ideas of adaptation to a new state in response to a disturbance. Bahadur *et al.*, (2010) presents a range of similar definitions found across a wide range of applications (Table 1-1), all of which incorporate concepts of resistance and bounce-back, as well as ideas of adaptive capacity or long term change.

However, of these stages of resilience, resistance and recovery are frequently the focus during responses to hazard events such as floods (Davoudi, 2014). For example, the UK Environment Agency (EA) 2018 information campaign regarding flood resilience carries the strapline "*Prepare, Act, Survive*" (https://floodsdestroy.campaign.gov.uk/). This statement is a clear focus on the resistance of individuals and communities to flooding, and the survival of their pre-existing situation in the aftermath. A focus on emergency response is also reflected in the Cabinet Office definition of community resilience as "*communities and individuals harnessing local resources and expertise to help themselves in an emergency, in a way that complements the response of the emergency services*" (Cabinet Office, 2011, p. 11). Recent national policy has also reflected this response and recovery focus. The UK National Flood Resilience Review (HM Government, 2016) focuses on the resistance of critical infrastructure to flooding, and how quickly services can be returned to normal following a flood event. The companion Property Flood Resilience Plan (Bonfield, 2016, p. 4) focuses on residential property and the installation of measures to "*help prevent flood water ingress into a building or aid rapid recovery*".

Table 1-1. Definitions of resilience from a range of UK and international organisations

"*The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner*"
United Nations International Strategy for Disaster Reduction (2009)
"*The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change*"
Intergovernmental Panel on Climate Change (Solomon et al., 2007)
"*The capacity of a system to absorb disturbance and reorganize while undergoing change*"
The Resilience Alliance (Walker et al., 2004)
"*the ability of countries, communities and households to manage change, by maintaining or transforming living standards in the face of shocks or stresses - such as earthquakes, drought or violent conflict - without compromising their long-term prospects*."
UK Department for International Development (2011)

Edwards (2009) argues that this focus on response and recovery is because UK resilience policy is grounded in command and control thinking, something which Manyena (2006) argues is common for disaster resilience programmes globally. The need for measurable metrics and the demonstration of effective management integrates easily with the response and recovery aspects of resilience, which are easily controlled and measured, for example how long it takes a flood-affected family to return to their homes. Emergency response also integrates well with the focus on individual self-reliance highlighted by Davoudi (2016). Individuals and households can be encouraged or instructed to prepare, through information campaigns such as "Prepare, Act, Survive", and these efforts can be coordinated from the top-down to integrate with the actions of the emergency services (Cabinet Office, 2011). In contrast, developing long-term adaptation based resilience requires a hands-off, locally-driven approach which Edwards (2009) argues cannot be easily measured, controlled, or directly affected by government expenditure.

As the governance of flood risk management has shifted from institutionally controlled flood defence towards more holistic management focused on individualised resilience, so the role of management organisations has also changed (Nye et al., 2011). To encourage at-risk individuals and communities to accept their role in risk management, and to encourage them to adopt protective, resilient behaviours, the provision of risk information has become a key part of managing risk (O'Sullivan et al., 2012). Self-reliance is a key aspect of developing resilience and hence intervention by management organisations is considered to obstruct the role of communities and individuals in taking personal action (Risk and Regulation Advisory Council, 2009). Management organisations therefore take on the roles of educator or instructor, rather than active partner or participant. The Strategic National Framework on Community Resilience sets out the role of central government specifically as that of "*'motivating' and 'incentivising' (Cabinet Office, 2011, p. 6), 'supporting' and 'enabling' communities to help themselves (Cabinet Office, 2011, p. 7)*" (Cabinet Office, 2011 quoted in; Bulley, 2013, p. 267).

1.4.4 Fostering community resilience: educating the public about flood risk

In the context of community resilience to flooding, flood risk communications are a key tool in this programme of motivating, supporting, and enabling preparedness and response to floods (Butler and Pidgeon, 2011). O'Sullivan (2012) argues

> "*flood risk communication serves to ensure that* […] *the public will behave in a way where appropriate and effective steps to reduce and mitigate the risk are taken*" (p. 2271)

The UK provides a good example of the flood communications currently being developed across Europe (de Moel et al., 2009; Van Alphen et al., 2009). These are focused on the communication of long term flood hazard information, such as maps showing areas potentially at-risk (Hagemeier-Klose and Wagner, 2009), and the provision of information on floods as they occur, such as flood warnings. The former is intended to promote long term preparedness for floods, whilst the latter is intended to prompt short term activities such as implementing flood plans or undertaking evacuations (de Moel et al., 2009).

The role and success of flood risk communications in promoting resilience at an individual or community level is contested. Research from psychology identifies complex pathways by which risk messages are translated in to action, affected by a wide range of factors and experiences which include: previous experiences of a threat, which can result in either a positive (Fielding et al., 2007) or negative influence on protection motivation (Hopkins and Warburton, 2015); reliance on public flood protection (Terpstra and Gutteling, 2008); a conflict in perceived responsibility between flood management organisations and the public, including trust/distrust in communications from a management authority (Terpstra, 2011; Wachinger et al., 2013); and finally a need to protect an individual's sense of personal security in the face of high levels of future uncertainty (Harries, 2008).

Flood communications are central to the development of resilience and are exclusively expert-driven and created on the basis of complex numerical models hidden from public knowledge or scrutiny (Lane, 2012). Local knowledge is typically excluded from these expert analyses, with flood affected communities playing little or no role in re-assessing flood knowledge after floods occur (Lane et al., 2011b). Thus, management organisations position themselves simultaneously as both responsible for FRM, through controlling knowledge and information flow, and yet unaccountable, through their transfer of risk onto communities with its expectation of resilience development (Deeming et al., 2012; Lane, 2012). This situation can cause significant conflict between communities and management authorities when official knowledges demonstrated through formal flood maps, based on generalised numerical modelling and remote sensing, do not reflect, or allow for, local knowledges, based on personal and highly localised experiences (Lane, 2012; Meyer et al., 2012, 2011). Lane (2012) argues that this hierarchical asymmetric relationship between those who manage risk and those who have to live with it develops upwards dependence and damages the development of local capacity to cope with floods, as well as generating conflict or controversy between authorities and flood-affected communities.

1.4.5 Fostering community resilience: an unsustainable mechanism for flood risk governance?

This asymmetric relationship between management organisations and the public supports the bounce-back focused resilience which has dominated recent resilience policy. By controlling public access to information on flood risk as a privilege of 'experts' (Lane, 2012), floods continue to be popularly represented as occasional, aberrant, and extreme occurrences which are not, or cannot, be dealt with by the general public (Terpstra and Gutteling, 2008). This clearly maps onto the concepts of resilience as preparedness and short term emergency response, intended to lessen immediate hazard impacts and speed up the return to normality (Davoudi et al., 2013). This focus on the maintenance of normality, maintains and reinforces the normative practices of traditional flood management which privileges expert knowledge and exclude 'lay people' from the production of risk knowledge or any active role in risk management (Swanstrom, 2008). It also obstructs ideas of transformational change and adaptability into the application of expert-led standardised procedures, and top-down command and control management approaches (Davoudi, 2014; Manyena, 2006). As Bulley (2013) argues, this is intended to maintain top-down control over local flood management governance. This has the effect of restricting what individuals and communities can meaningfully do to become resilient to a pre-determined set of options within the comfort zone of traditional management (Davoudi, 2016). Not only does this restrict the development of resilience, it is also at odds with wider policy drivers for integrated management, such as the WFD and Floods Directive, that promote equitable access to environmental decision-making, and the long-term adaptation of communities to cope with a changing environment (Urwin and Jordan, 2008).

These implementations of resilience are no more sustainable than the traditional flood defence approaches which dominated early flood management; in the face of a changing climate, we can no more afford to maintain 'normality' than we can to continue to build higher flood defence walls.

1.4.6 Renewing the governance of flood risk management: integrating participation and resilience

In contrast to established practices of resilience, which focus on a return to normality following a disturbance, and then a subsequent period of adaptation, Davoudi (2012; 2013) proposes a new form of resilience. So called 'evolutionary resilience', also often referred to as socio-ecological resilience (Abdulkareem et al., 2018) or social resilience (Maclean et al., 2014), builds on the resistance-recovery-adaptation model of resilience laid out by ecological resilience theory (Holling, 1973). Evolutionary resilience incorporates the human capability to anticipate and prepare (Davoudi et al., 2013), shaping not just the solution but also the problem (Swanstrom, 2008). By incorporating ideas of preparedness, ecological resilience

> "*promotes the institutionalization of awareness of adaptability dynamics as a way of enhancing preparedness and with it, the capacity to influence the direction of future transformations*" (Davoudi et al., 2013, p. 319).

This conceptualisation of resilience can be seen to upend the traditionally asymmetrical relationship between management organisations and at-risk individuals and communities. Preparedness is promoted not just as a shallow concept aimed at enhancing bounce-back, but as the genuine implementation of participation within the local governance of hazards; where knowledge, skills, and ongoing learning at a local level form a key component of a resilient, adaptable social system (Maclean et al., 2014). In this conceptualisation of resilience, the achievement of resilience is not a goal or metric, but an ongoing internal process at the local scale (DeVerteuil and Golubchikov, 2016) in which change and transformation build social, economic and environmental strengths (Shaw, 2012). Ecological resilience also repositions hazard events as everyday occurrences, integrated into the fabric of society and adapted to in the same way as long-term 'slow-burning' internal changes (Davoudi, 2012).

Adopting this conceptualisation of resilience requires challenging the established governance structures and practices of flood and catchment management which maintain existing expert-lay hierarchies and obstruct the development of local level knowledge, skills, and adaptive capacity. To do this, research must explore how existing practices shape ideas of integrated management, participation and resilience. By considering how these concepts are defined, by whom, and for whose benefit, we can rethink the relationship between individuals, communities, and management organisations in the management of the environment in the future. The complexity of the interactions represented by these questions constitute a messy or 'wicked' problem (Donaldson et al., 2010), the result of which is that individual aspects are typically explored in isolation from each other by individual disciplines (Bracken et al., 2015).

1.5 Thesis structure

The thesis is structured using the following five chapters:

Chapters 3 and 4 have been published in international peer-reviewed journals, whilst Chapter 2 is in review for publication. For each paper, an overview of the motivation for the paper, the citation information, and the author contributions are outlined at the start of each chapter.

Chapter 2 presents the findings of research on the nature of Integrated Catchment Management and its practices of participation in a UK context. This chapter explores the themes of catchment management governance, current practice in integrated catchment management, and the respective roles of expert institutions and communities in the everyday management of the water environment. Working together with an innovative catchment partnership in the northeast of England, and with communities within the catchment, the research collects data on the practices of management from a 'top-down' and 'bottom-up' perspective. The data collected, using a diverse, mixed methods approach grounded in participation and participant observation, explores how policy and governance drivers influence the practices of participation in UK catchment management. The research demonstrates how supra-catchment scale drivers continue to dominate management practices, privileging traditional scientific and expert knowledge and excluding local communities. The research argues for a re-imagining of catchment governance and demonstrates how communities can be meaningfully integrated into existing and emerging practices of knowledge creation and management.

Chapter 3 presents the findings of research on rethinking the role of at-risk communities in existing expert-led practices of scientific knowledge creation. This chapter discusses the relative roles of expert organisations and at-risk communities in the practices of FRM, using the traditionally expert driven practice of numerical flood modelling as a case study focus. This chapter examines the relationship between local and official knowledges and demonstrates how, by bringing different perspectives together, new, more effective practices of knowledge creation can be established. Working together with a flood-affected community in the northeast of England, the research collates a detailed Volunteer Geographic Information (VGI) database detailing the dynamics and impacts of a flood which occurred in winter 2015. The research then integrates this non-standard data into the validation of a numerical flood model, constructed using the LiSFLOOD-FP (Bates and De Roo, 2000), developing a framework for holistic validation of complex two dimensional flood models. The research demonstrates how opening up established practices of knowledge creation, such as flood modelling, to alternative data, knowledge or perspectives can enhance existing practices of knowledge creation for both management agencies and communities.

Chapter 4 presents the findings of research on the establishment of new knowledge creation practices founded on the adoption of principles of participation. Using the communication of flood risk as a case study focus, the chapter considers how FRM practices conceptualise community preparedness and resilience as aspects of FRM, and how this is shaped by established, top down practices of management through the communication of risk information. Adopting a participatory approach, and working alongside an at-risk community, this chapter demonstrates how bringing together differing perspectives can reimagine how risk is conceptualised, and what information is important to who, and why. This strand of the research resulted in prototypes for communicating flood risk in new ways.

Chapter 5 is a discussion of the key themes which emerge from the individual papers and brings these together in the context of the principle research areas outlined above. Issues of governance, flood management practice, and the role of participation are discussed in relation to the emerging concept of 'living with floods' as part of the integrated management of the water environment.

Chapter 6 contains the primary conclusions and recommendations of the thesis.

1.6 Research approach

The research outlined in this thesis adopts a participatory approach (Breitbart, 2010; Kindon et al., 2007a, 2007b), translated into research practices through a pragmatic and diverse, mixed methods approach. It adopts a transdisciplinary approach (Bracken et al., 2015), attempting to break down the traditional border between physical and social science research areas with the aim of increasing the usability of the research for wider policy/implementation fields and incorporating alternative knowledges and expertise (Bracken et al., 2015). In this way the research utilises both social and physical science methods (Figure 1-2).

A range of methods were adopted throughout the research in order to explore different situations, participants, and relationships. The exact methods and data used during each stage of the research are detailed in the 'Methods' sections of

Chapters 2 to 4, but a broad summary of each method adopted by the research is provided below:

Ethnography and participant observation – This was undertaken following Atkinson and Hammersley (1994), and the methods were adopted to explore participants points of view, and what their actions or behaviours mean within the context of their environment, for example the influence of outside drivers (Gobo, 2011). This method is adopted predominantly in Chapter 2, through a collaboration with a catchment partnership made up of statutory and non-statutory management organisations to explore how regulation and visions for operationalising ICM policy are enacted in the study area. These methods were also extended to examining the perspective of the local communities within the study area in Chapter 2, participating in local social activities, such as the walking group and village hall café, to understand local knowledge of and engagement in the environment of the study area.

Interviews and Walking Interviews – To further develop the insights gained from participant observation, some participants in the research were also interviewed to gain deeper understanding of their knowledge and perspectives. Interviews were used in Chapters 2 and 3 and were predominantly semi- or unstructured, allowing the participants to set the agenda and discuss issues of importance to them. In both Chapters 2 and 3, interviews were also supplemented, following Dowling *et al.* (2016), with participatory mapping (see below) or by conducting interviews as walking interviews (Evans and Jones, 2011). The spatiality of knowledge, and peoples connectedness and sense of place (Stedman, 2003), is an important aspect of integrating people more effectively into the practices of management at a local scale. Undertaking interviews alongside participatory mapping, or out in the field, allows knowledge and experiences to be tied specifically to its spatial context by participants rather than being assumed by the researcher (Jones et al., 2008; Jones and Evans, 2012).

Participatory mapping – Participant-led mapping activities were undertaken following McCall (2008) and Talen (2000) in Chapters 2, 3, and 4 to collect and explore local knowledge and engagement with the environment. Using mapping alongside individual and group discussions allows traditionally marginalised environmental knowledge to be recorded and situating specifically within its spatial context (Dunn, 2007). Integrated with the principles of Participatory GIS (Wood, 2005) and Volunteered Geographic Information (Goodchild, 2007) in Chapter 3, allows data collected through participatory mapping to be integrated with traditionally regarded sources of spatial data for use in established practices of knowledge creation.

Numerical flood simulation modelling – To explore established practices of expert-led knowledge creation, flood simulation modelling was undertaken in Chapter 3 using LISFLOOD-FP (Neal et al., 2012). Development of a framework for the use of Volunteered Geographic Information in the validation of flood simulation models was used as a tool in understanding how official and local knowledge can be brought together to enhance existing practices of knowledge creation.

Competency group - The establishment and work of a flood research group modelled loosely on the concept of the Environmental Competency Group (Lane et al., 2011b) is employed in Chapter 4. This participatory group planned and undertook the research presented in this chapter, and the author worked together with the group as a member. Although the focus of competency groups is often the **process** of knowledge creation, following Lane *et al.* (2011b), the research presented in Chapter 4 also involved the creation of prototypes for new flood risk communications. Created jointly by the group, this activity brought together principles of participatory mapping (as above) and participatory diagramming (Kesby, 2000), in representing the final culmination of the participatory work and the creation of new, shared knowledge on flood risk communications.

Data review and analysis – review and analysis of the data collected during the research was carried out using a range of approaches, chosen based on a pragmatic and reflexive assessment of the data available. Predominantly, analysis adopted approaches based on grounded theory (Charmaz, 2011) or grounded visualisation (Knigge and Cope, 2006). Grounded theory is commonly adopted for the analysis of qualitative research outputs. The reflexive approach to simultaneous analysis and data collection, and the simultaneous development of theories is argued to allow the researcher to "*unravel the complexities of doing qualitative analysis and to understand mysteries and moments of human life*" (Charmaz, 2011, p. 165).

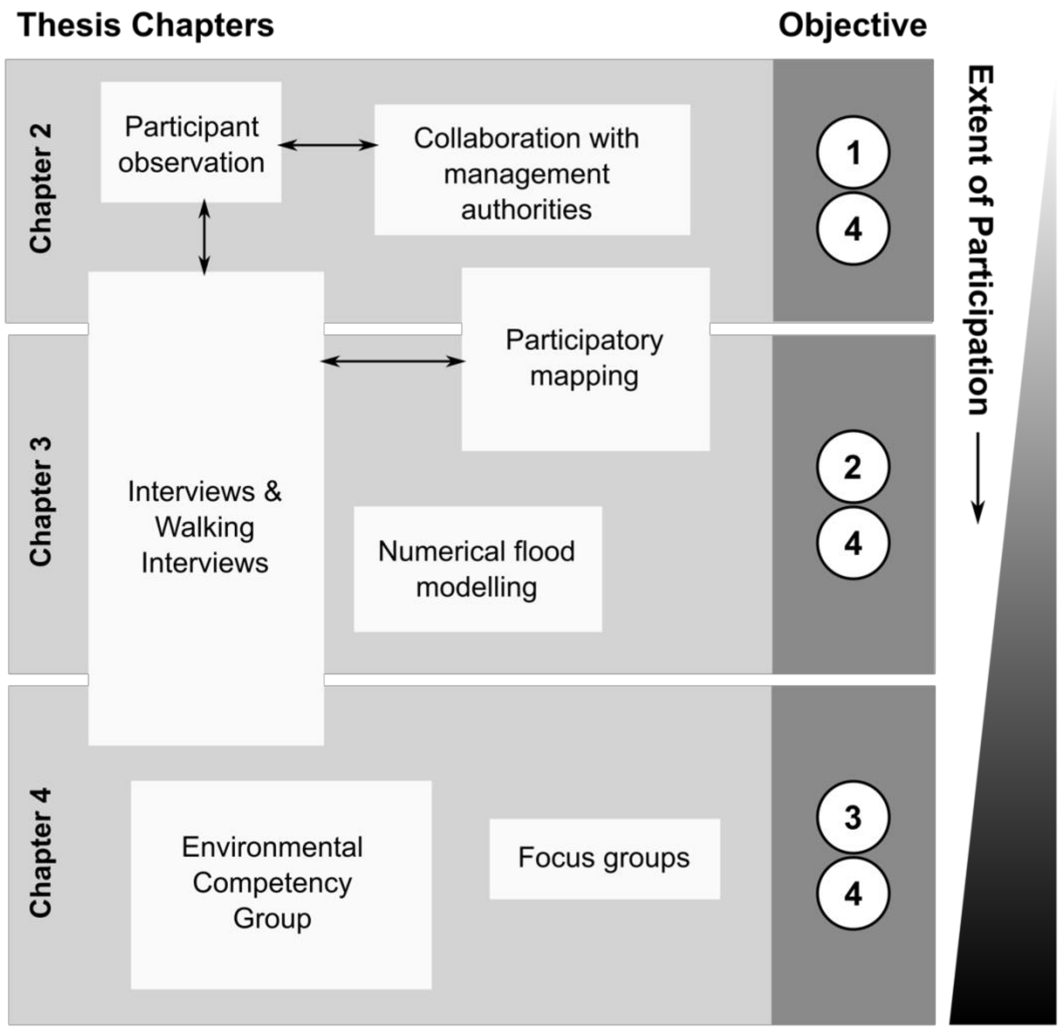


Figure 1-2 - The principle research methods adopted during the research, where they are situated within the thesis, and their application to meeting the objectives of the research. Arrows indicate integration or connectivity between the methods deployed, for example interviews conducted alongside mapping. Recommendations for how existing approaches to understanding and working together with local perspectives could be improved (Objective 4) are included within the recommendations made in each chapter, and are also brought together in the discussion presented in Chapter 5.

1.7 Summary

Flooding is a major hazard across Europe, and the last two decades have seen frequent major floods which have demonstrated that established strategies of flood defence based on hard flood defences are unsustainable. In response the way in which flooding is managed has evolved, with a greater focus on integrated management, citizen participation, and resilience. However, debates continue as to how effectively practices of management have shifted to match more participatory policy.

The research presented in this thesis explores this area, considering the interconnected foci of governance systems, public participation, and flood management. In contrast to other studies which have adopted a top-down **or** bottom-up approach to this issue, this research adopts an transdisciplinary approach to explore and develop alternative perspectives. The research adopts a pragmatic and dynamic mixed methods approach, blending social and physical science methods. By doing so, the research breaks down traditional barriers between research areas, exploring how alternative perspectives and knowledge of water management and flood risk can be understood and used, and how we can exploit new approaches to working collaboratively to generate new shared knowledge.

Chapter 2 Evaluating the success of public participation in integrated catchment management

Overview: This paper presents research exploring the nature of participation in catchment management practice, using the experiences of a multi-disciplinary catchment partnership established for a small sub-catchment in the northeast of England. The paper examines practices of participation from both a ‘top-down’ perspective, exploring the activities of the partnership, their motivations and drivers, and also a ‘bottom-up’ perspective, exploring local community knowledge about the catchment, and their emerging aspirations for local participation in environmental management.

Motivation: The purpose of this paper was to examine drivers of participation in Integrated Catchment Management, and to explore whether the recent changes in supra-catchment policy had succeeded in embedding participatory practices at the local level. The findings of the research presented in this paper helped to establish the foundations for the subsequent participatory research.

Citation Information: This chapter was published in the Journal of Environmental Management as Rollason E, Bracken LJ, Hardy RJ, Large ARG (2018) Evaluating the success of public participation in integrated catchment management. Journal of Environmental Management 228:267–278. doi: 10.1016/j.jenvman.2018.09.024

Author Contributions: In this paper, I designed the research methodology, undertook the empirical data collection, wrote the text, created the figures and led the paper development. My co-authors provided editorial input and guidance on the development of the paper.

2.1 Introduction

The past two decades have seen increasing global efforts to adopt more holistic and integrated approaches to manage water environments (Watson and Howe, 2006), for example in Australia (Bellamy *et al.*, 2002), Africa (Dungumaro and Madulu, 2003), the USA (Ballweber, 2006), and across the EU (Mouratiadou and Moran, 2007). Commonly referred to as Integrated Catchment Management (ICM) (Lerner and Zheng, 2011), these approaches use hydrological catchments as natural organising units for interventions in the landscape and natural processes (Fenemor *et al.*, 2011). They are typified by the replacement of often fragmented and sectorally distinct approaches (Butterworth *et al.*, 2010; Watson *et al.*, 2009) with new, integrated land-water practices grounded in participation, shared knowledge, and social learning (Allen *et al.*, 2011; Mitchell and Hollick, 1993; Watson and Howe, 2006).

As ICM approaches have become more widely adopted (Rouillard and Spray, 2017), studies have reported success in implementing ICM principles (Collins *et al.*, 2007; Cook *et al.*, 2013a). However, current research is focused predominantly on the supra-, or large catchment scale, and has typically adopted a top-down perspective (Sabatier, 1986) to assessing how effectively policy has been implemented (Watson, 2014). This has resulted in a gap in our understanding of ICM implementation at the local, or sub-catchment, scale (Mees *et al.*, 2017), where issues have been raised about how meaningful and extensive ICM-based participation is (Mouratiadou and Moran, 2007), and whether participatory policies can overcome traditional practices of management (Cook *et al.*, 2013b; Watson, 2014).

The purpose of this paper is to address this existing research gap by exploring the nature of integrated management practices at the local scale. In particular we look to determine how supra-catchment drivers of participation are translated into local participatory practices, and how these practices impact on communities within the catchment area.

In contrast to previous research we adopt both a ‘top-down’ and ‘bottom-up’ approach to explore the governance arrangements and working practices of a catchment management partnership, and the knowledge, experiences, and aspirations of the communities living within the area. To undertake this analysis we use the case study of a sub-catchment scale management partnership in the Northeast of England. We adopt a pragmatic, mixed methods research approach grounded in the concepts of participatory research, intended to engage with and explore a range of differing perspectives on catchment management and participation. This aims to (i) examine how the catchment partnership functions and how catchment interventions are identified, planned, and implemented; (ii) explore how community participation is conceptualised, and how it is enacted through the practices of management demonstrated by the partnership; and (iii) explore how local communities and individuals conceptualise their environment and how it should be managed, and how this interfaces with the work of the partnership.

The research presented is some of the first to consider interactions between local communities and management agencies in the day-to-day management of the environment, and how more active community participation can contribute to more effective ICM. This research is therefore crucial to determining if aspirations for community engagement are being met, and what barriers and opportunities exist for integrating people and communities into ICM practices at the local scale.

In the next section we explore ICM, and public participation in management, in more detail.

2.2 Background to ICM

ICM as a term is often left purposefully generic, such as the definition adopted by Lerner and Zheng (2011) as "*the fully integrated management of the land, water and human activities in* […] *catchments*" (p. 2638). This reflects the multiple objectives of ICM and the way in which it is operationalised (Butterworth *et al.*, 2010). Taking a more detailed perspective, Kilvington *et al.* (2011) and Varis *et al.* (2014) argue that ICM represents two fundamental principles: horizontal integration, across and between management organisations from different disciplines, for example flood risk, spatial planning, or agriculture; and vertical integration between experts, policymakers, and the public. Here, we review the vertical integration component of ICM, exploring how traditional and ICM approaches to management differ in how they integrate public participation into environmental decision-making.

We acknowledge that public participation in environmental decision making is not a new phenomenon, and did not emerge specifically with a proposed shift towards ICM approaches (Reed, 2008). However, the ways in which traditional catchment management and ICM integrate people into practices of management are distinctly different (Eden, 1996). Participatory activities in traditional management are characterised by hierarchical arrangements, the dominance of expert-led decision making, and asymmetrical power relationships between management agencies and the public (Lane, 2012; Watson *et al.*, 2009). In these circumstances participation is often heavily controlled and choreographed, and usually intended to identify public preferences for, or to 'sell', a preferred option (Warner, 2011). In contrast, ICM is characterised by a philosophy of participation aimed at dispersing and localising decision-making power (Marshall *et al.*, 2010; Mitchell and Hollick, 1993) and combining officially sanctioned, scientific knowledge with local knowledges and perspectives (Jemberu et al., 2018; Stringer and Reed, 2007). Participation in this context is not a mechanistic target to be achieved, but an ongoing **process** which represents a fundamental part of catchment management activities (Reed, 2008).

The participatory nature of catchment management is often evaluated using conceptual models, such as Arnstein's (1969) 'Ladder of Participation'. This model classifies participation on a continuum between manipulative non-participation through to total citizen control. However, Collins and Ison (2009) argue that the model represents an over-simplified, power-focused model of participation and hence fails to consider the complex, and often non-linear, interactions between agencies and communities over time (Tritter and McCallum, 2006). In this way failure is implied if total citizen control is not obtained, even though a model of total citizen control is not always desirable or achievable (Hayward *et al.*, 2004).

Plummer and Fitzgibbon (2004), drawing on Berkes (1994) and Pomeroy and Berkes (1997), proposed a multi-dimensional model of co-operative management () which extends the original power-relationships concept by exploring the interrelationships between representation, power and process. This model also considers which bodies achieve representation and the nature of participatory processes. Assessing participatory activities against power, representation and process builds on criticisms of Arnstein's original ladder, acknowledging the additional complexity of who participates and how. In this paper, we use this model to assess the degree and nature of participation in ICM.

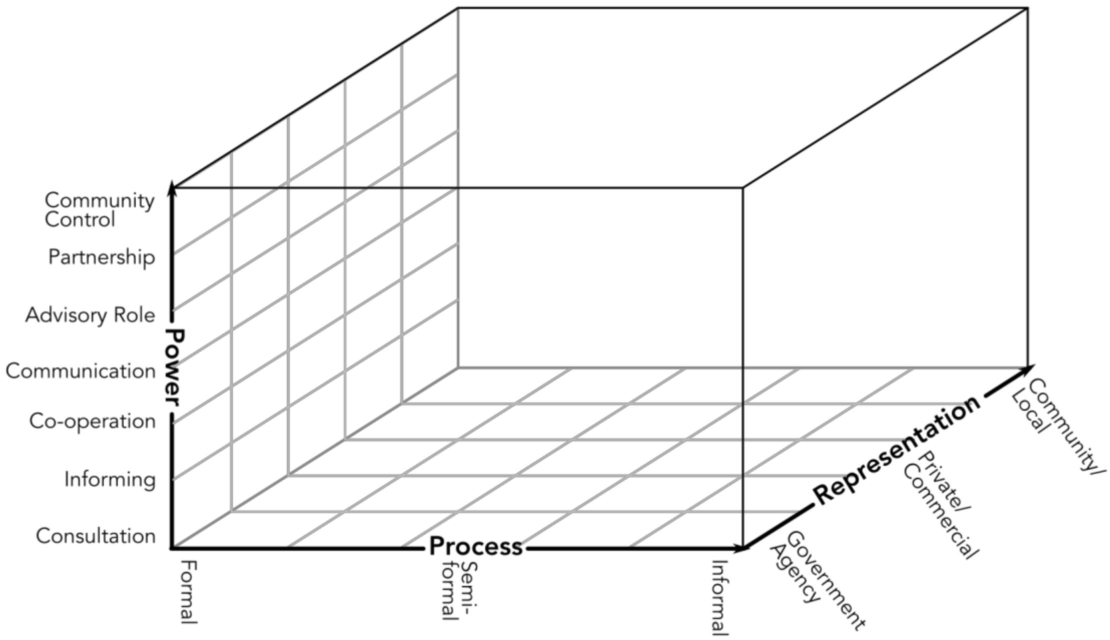


Figure 2-1. Plummer and FitzGibbon's (2004) conceptual model of co-operative management. The degree of participation is assessed dependent upon and the formal or informal nature of the processes adopted (x axis), the degree to which power is transferred between groups (y axis), and which groups achieve representation (z axis) (Adapted from Plummer and FitzGibbon, 2004; and Pomeroy and Berkes, 1997).

Policy frameworks have evolved to embrace ICM and encourage public participation. The EU Water Framework Directive (WFD) focuses on both the integrated management of catchment systems (Watson and Howe, 2006) and public participation (Fritsch, 2017; Nones, 2015; Robins *et al.*, 2017). Article 14 of the WFD requires public information supply and consultation through formal processes and encourages public participation in implementing interventions. The WFD also states that "*more* [public participation] *may be useful to reach the objective of the directive*" (Newig *et al.*, 2014, p. 279), and so participation is expected from the general public and not just the relatively small pool of expert stakeholders typical of traditional management (Reed, 2008).

Expectations for engagement in practice can be explored by examining how the WFD is translated into policy across the EU. In England, the WFD has been translated into national policy through CaBA (Defra, 2013; Harris, 2013; Watson, 2014). This policy was intended to effectively implement the public engagement principles, linking high level policy to local level practice (Harris, 2013; Starkey and Parkin, 2015; Varis et al., 2014). CaBA envisions the management process as a series of nested and integrated practices operating at different scales. Three scales are identified, each characterised by differing approaches to participation. The highest, supra-catchment, scale is the national or a river basin scale, of which there are 11 in England and Wales (Watson and Howe, 2006). CaBA work at this scale is dominated by expert-led management organisations and participatory focus is on informing and consulting (Figure 2-1). The second scale is that of the individual catchment, 80 of which are defined under the WFD in England and Wales (Defra, 2013). This is the scale at which the majority of CaBA activity is focused because it has been argued that this is "large enough to add value at a strategic scale but small enough to encourage and support local scale engagement and action" (Defra, 2013, p. 10). Management tends to be undertaken through Catchment Partnerships (CPs) which act as collaborative fora for diverse catchment stakeholders including local authorities, management agencies, and third sector organisations representing local groups or specific issues (Harris, 2013). The third, and smallest, scale is the sub-catchment or local scale. This consists of individual locations or communities where the practices of management are applied and where individual catchment interventions are implemented. Management activities are usually undertaken by the higher level catchment partnership, however in practice in the UK and elsewhere some sub-catchment partnerships have also been formed specifically to address local issues (Environment Agency, 2015). The catchment and sub-catchment (local) scale are where participatory activities are intended to occur, including "*identifying, planning and acting* […] *with a range of* *stakeholders and members of the public as appropriate*" (Defra p. 6). Participation is characterised by increasing degrees of local control (Figure 2-1 Advisory Role upwards), with CaBA guidance stating that participatory practices at this scale should include direct citizen involvement in both plan making and the local implementation of interventions (Defra, 2013).

ICM has therefore emerged as a mechanism for horizontal and vertical integration, embedded within EU and UK catchment management policy, and CPs have developed as collaborative fora for its implementation. However, outside of exploring horizontal and vertical integration within relatively formal structures of management there has been relatively little study of how effectively policy frameworks such as CaBA (Figure 2-2) implement vertical integration and community participation on the ground (Cook et al., 2013b, 2013a, 2012). Here, we look to explore this issue, working together at the sub-catchment (local) scale both with a ICM partnership and with the communities occupying the catchment being managed. We look to examine vertical integration between the partnership and affected communities, exploring how practices of participation are enacted, and the influence of internal and external drivers.

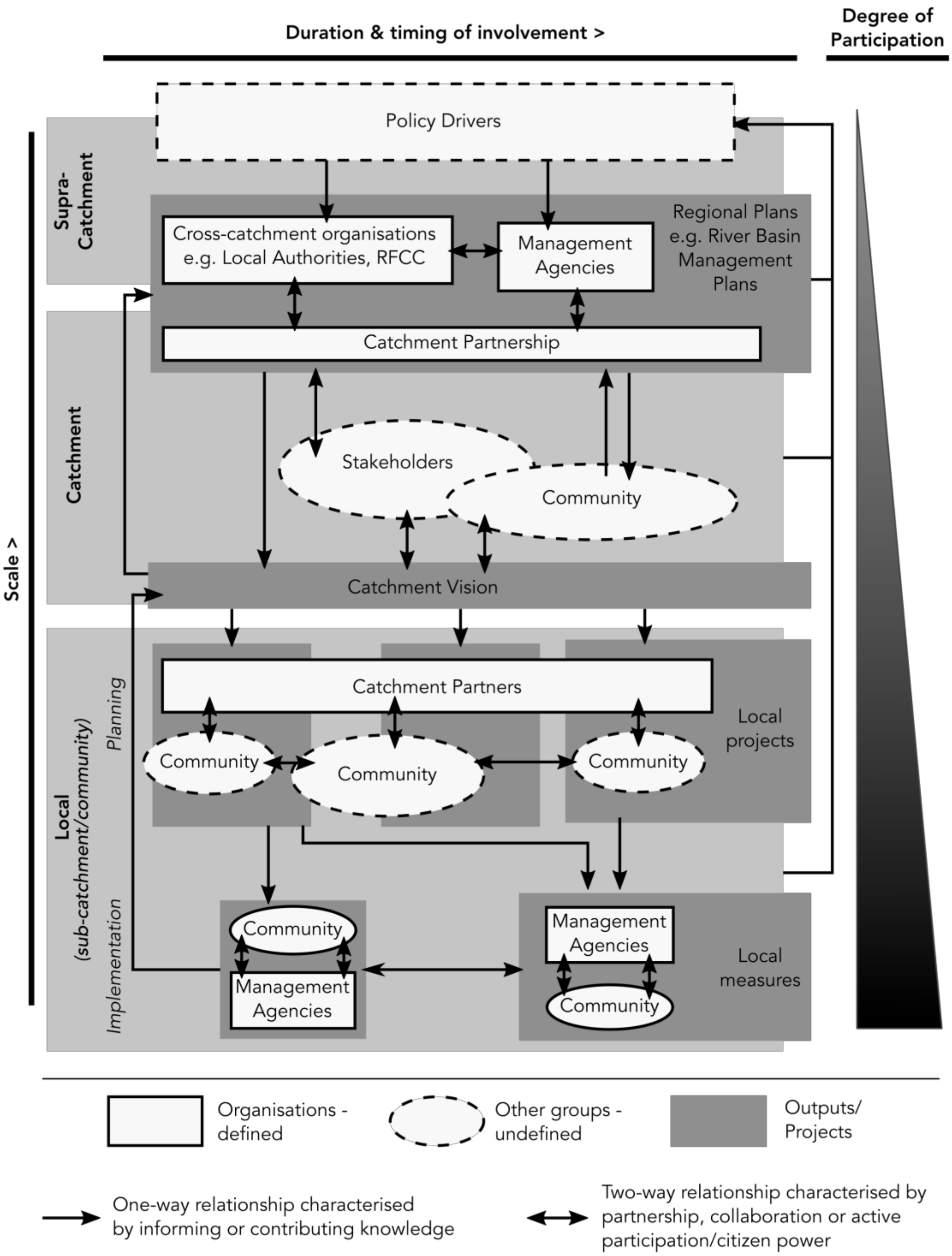


Figure 2-2. A conceptual model showing the principle drivers, outputs, organisations, and the participatory nature of their relationships which underpin Integrated Catchment Management as conceived through the UK Catchment Based Approach. The x axis indicates the broad duration and timing of different relationships, whilst the y axis indicates catchment scale.

2.3 Methods

2.3.1 Research Approach

In 2015-16 research was undertaken to explore ICM practices implemented by a catchment partnership in northeast England (see Section 3.2). We explored both top-down and bottom-up perspectives using a mixed-methods approach which drew on research into participatory working with catchment groups (Bracken et al., 2016; Lane et al., 2011b; Waterton et al., 2011; Whitman et al., 2015) and acknowledged the importance of exploring and understanding community-based knowledges (Bracken *et al.*, 2015). The range of methods was invaluable in gaining community trust, identifying research participants, and obtaining a wider understanding of community concerns and aspirations.

2.3.1.1 Data Collection

Our focus was on recording and understanding the work of the catchment partnership and its relevant partners (see Supplementary Information), but also local knowledge, attitudes and aspirations of the communities within the area (Section 2.4). To do this we adopted a pragmatic, mixed-methods approach to collect as wide a range of data as possible (Table 1).

Participatory mapping (McCall, 2008) and walking interviews (Evans and Jones, 2011) were used to explore individual's local knowledge and experiences within the context of their local environment.

Participatory mapping has been shown to be a valuable tool in assessing local needs and analysing local problems, perceptions, and priorities (Dekens, 2007). Participatory mapping was conducted on an individual basis, in the form of unstructured interviews, and through open workshops and drop-in sessions at existing community events. The majority of participants in these sessions were male, aged between 44 and 65, and retired, although they came from a variety of professional backgrounds. This reflects both the composition of the communities within which the research took place and also the availability of participants during the research period.

Table 2-1 - The research methods adopted during the study and the data collected. Data was collected predominantly between spring 2015 and summer 2016 during fieldwork in the Twizell Burn Catchment and with the Greening the Twizell Partnership (see Section 2.3.2).

Data Type	Source	Quantity/Data
Participatory Mapping	Interview transcripts and annotated mapping (transferred to GIS data by researchers) from one-to-one participatory mapping interviews.	4
	Annotated mapping and text comments (transferred to GIS data by researchers) from participants at three drop-in sessions held in support of partnership activities	Three drop-in sessions held at local community centre to support partnership activities.
Walking Interviews	Interview transcripts and GPS trace of route from walking interviews. Supported by post-interview notes taken by researcher.	2
Community Ethnography	Ongoing community participation between December 2015 and March 2016, including attending community cafes, and participation in community walking groups.	Ongoing note-taking from researchers about their interactions with community members.
Ethnography	Participation in Catchment Partnership activities between May 2015 and September 2016. In particular attendance at Steering Group meetings and involvement in the planning and/or implementation management projects.	Ongoing note taking from researchers Notes from meetings Reports and documentation from management agencies

Discussions were participant-driven, using the theme of ‘what do you know about the environment of the Twizell Burn?’ as a broad introductory framework, and with a hard-copy map of the local area to provide context and an aid to discussions. Participants were encouraged to discuss their knowledge and opinions, using the map as a prompt, with locations or extents hand drawn on the maps and annotated. Additions to the maps were digitised and integrated with transcribed discussions to produce a qualitative GIS as proposed by Cope and Elwood (2009). Interview discussions were audio recorded, although discussions at drop-ins and community workshops were not, with the interviewer indicating locations on the map to which the discussions could be linked during analysis. The locationality of knowledge was the principle focus of the interviews and other discussions and recording this effectively was therefore essential. Formal recording or analysis of participants speech, for example voice tone or emotions, was not carried out as this analysis would not have been applicable to the wider dataset due to the diverse nature of the interactions, with some being recorded and transcribed and others not.

Participatory mapping was supplemented by 'walking interviews'. These enabled explorations of how knowledge and experience was situated or concentrated within different parts of the catchment through physically placing participants within their environment (Jones *et al.*, 2008). Walking interviews were also unstructured, with the routes of walks determined by the interviewee, natural go-alongs (Kusenbach, 2003) or participatory walking interviews (Clark and Emmel, 2008) using the typology developed by Evans and Jones (2011). Walking interviews were undertaken on a one-to-on basis. Interviews were GPS-tracked and audio-recorded to allow subsequent locational analysis of participant's knowledge during data analysis, as demonstrated by Jones and Evans (2012). Employing these methods allowed discussions to be free and participant-focused and uninterrupted by note taking.

Where possible we also undertook less structured ethnography. This included using local community spaces such as community centres to informally discuss the research activities with local residents, staff and patrons. We also participated in meetings of the catchment partnership, engaged in the planning and development of several catchment interventions and participated in a regular walking group. In this way our research was grounded in the principles of ethnography and participant observation, qualitative methodologies based on the observation and participation of researchers in the activities being studied (Atkinson and Hammersley, 1994). These methods enabled researchers to explore participants' points of view and what their actions or behaviours meant within the context of their environment (Gobo, 2011).

No formal data recording took place during the ethnographic research. Instead, the researchers maintained detailed field notebooks of interactions that focused on who had participated in discussions, the main interactions between different individuals and organisations, and how decisions were made. Notes were supported by examination of official meeting minutes and documents arising from the work of the catchment partnership.

2.3.1.2 Data Analysis

The empirical data collected during the study (Section 4) represented an unstructured and highly diverse, 'format messy' dataset consisting of locational data, transcripts of interviews, participatory mapping, and official documents. The nature of the dataset, whereby data on particular locations or regarding particular issues might be drawn from multiple sources and/or data formats made the adoption of a single, formal method of analysis difficult. To analyse these data we therefore adopted a pragmatic, grounded theory and grounded visualisation approach following Charmaz (2011) and Knigge and Cope (2006). This approach looks to integrate diverse empirical material in a flexible, and reflexive, way both during and after the data collection. The focus of the analysis was on identifying key knowledge and themes to explore the practices of management demonstrated and experienced by local communities.

2.3.2 The study area: The Twizell Burn Catchment

The research was undertaken in the Twizell Burn, a tributary of the River Wear located in northeast England, UK (Figure 2-3), an area managed by the Wear Catchment Partnership; a catchment organisation established officially under the CaBA. The catchment is mixed urban-rural and is heavily influenced by historic mining activity, both deep pits and more recent opencast. The water environment reflects its history: it is classified under the WFD as heavily modified and achieves only moderate ecological status (Environment Agency, 2018) as a result of sewage outflows, agricultural pollution, and the dewatering of historic mine workings (Groundworks NE & Cumbria, 2015). There is a history of management intervention in the upper catchment to remediate the effects of historic mining activity (Jarvis and Younger, 1999).

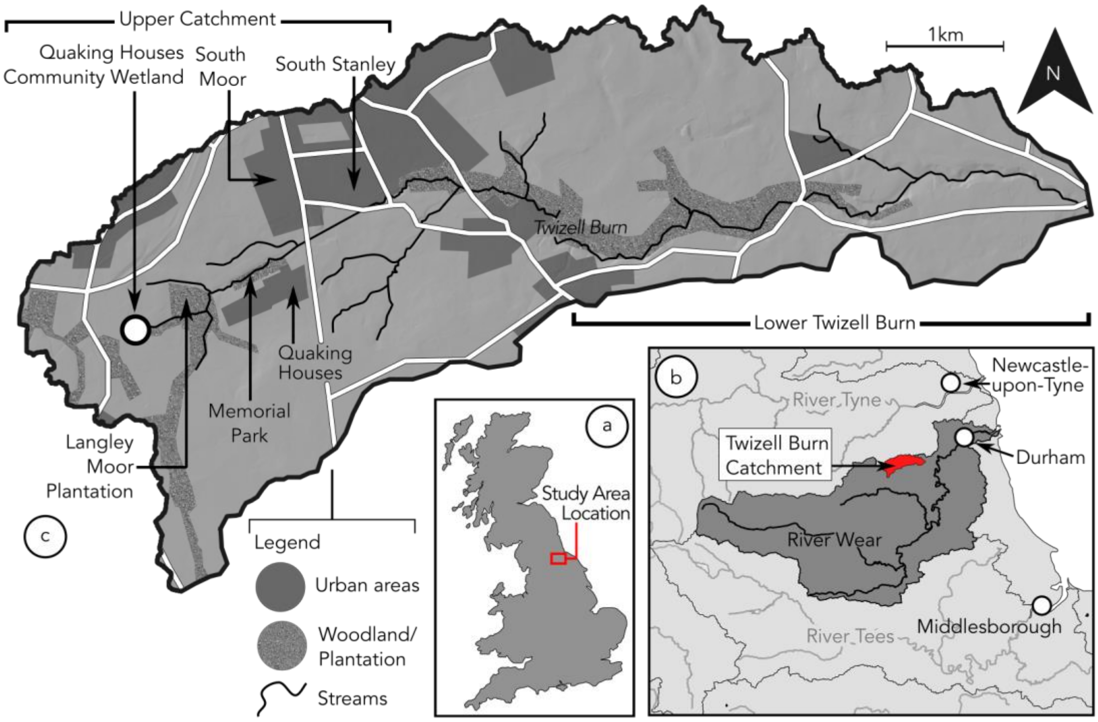


Figure 2-3. (a) The location of the study area within (b) the catchment of the River Wear, and an overview of the Twizell Burn catchment showing the location of places referred to in the text.

2.4 Results

In this section we initially adopt a top-down perspective to present the governance structures which shape management within the catchment, and the practices of management shown by the agencies working through a local partnership. Secondly, we adopt a bottom-up perspective, to present the viewpoint of the local community, focusing particularly on local knowledge and engagement with the catchment of the Twizell Burn, and the interactions of local participants with the activities of the partnership.

2.4.1 Catchment governance: establishing the Greening the Twizell Partnership

In 2015 Durham County Council (DCC), the local spatial planning authority, commissioned Groundworks NE & Cumbria (Groundworks), a local third sector organisation, to prepare a Green Infrastructure Masterplan for the Twizell Burn. The aim of this plan was to develop an integrated strategy for how the catchment should be managed by the diverse range of agencies with management duties or interests in the area (Groundworks NE & Cumbria, 2015). This work was founded on a period of public consultation, undertaken by Groundworks between October and December 2015. This consultation included four public meetings and an online questionnaire survey undertaken with communities across the catchment and in urban areas immediately adjacent; approximately 100 people were engaged by this process (Groundworks NE & Cumbria, 2015). Four workshops were also held between professional and community organisations within the area. Information derived from the exercise was used to develop the Green Infrastructure Masterplan, which identified a wide range of potential opportunities for integrated management of the Twizell Burn catchment (Groundworks NE & Cumbria, 2015). A key proposal was to establish a sub-catchment based partnership, the 'Greening the Twizell Partnership' (GtTP), charged with delivering the proposed management interventions. The aspiration of the partnership reflected both the ethos of collaborative management laid out in the CaBA, but also the participatory philosophy of wider ICM concepts:

> "*The purpose of the Partnership is to be* ***representative of stakeholders and the community*** *who are interested in making a difference in the Twizell catchment area* [and to] ***work together*** *to* […] *meet the vision and objectives for the Twizell burn*" (Groundworks NE & Cumbria, 2015, p. 126 - emphasis added).

The GtTP was established in 2015 and was initially chaired by the Wear Rivers Trust (WRT), a local third sector environmental organisation and chair of the River Wear Catchment Partnership, the CaBA partnership at the spatial scale above that of the study area. Other partners included the Environment Agency (EA) and Northumbrian Water Group (NWG), Durham County Council (DCC) and Stanley local town council. The partnership was supported by an engineering firm, Fairhurst Environmental, contracted by DCC, and Groundworks. Public representation was through the attendance of two elected local councillors, one of whom took over as chair of the GtTP steering group in 2017. Further information on partner organisations can be found in the Supplementary Information to this paper.

The GtTP's aim, outlined in the partnership agreement was:

> *"to improve environmental sustainability in the area surrounding the River Twizell through community engagement, and collaborative working between relevant organisations and institutions."* (GtTP, Personal Communication)

2.4.2 Catchment Management Practices: who participated and how?

Six principal interventions were planned and/or implemented by the GtTP during the research period (for details see Supplementary Information). Of these, two were 'bundles' of interventions comprising smaller interventions connected either by location, in the case of the South Moor Regeneration Works, or by focus, in the case of the Upper Catchment Works.

The interventions were predominantly carried out by two bodies: WRT undertook works focused principally on water quality and biodiversity in the lower parts of Twizell Burn (Fish Passage Works and Habitat Improvements) and distributed across tributaries in the upper catchment (Upper Catchment Works). Works by DCC, working together with Fairhurst Environmental, centred on the area of South Moor. These works concentrated on the general rehabilitation of the urban area including housing regeneration, the retrofitting of Sustainable Drainage Systems (SuDS), with multiple benefits including greening a high density urban area with improvement of downstream water quality and the installation of a heritage trail to illustrate the area's World War 1 heritage.

The practices of participation were distinct between the two agencies. Some limited consultation was undertaken by the WRT with the local angling club to identify locations within the lower Twizell Burn where habitat improvements and the installation of fish passes were necessary. This was informal and based on private contacts between WRT and the angling club; there was no public involvement in the detailed planning and implementation of these measures. In the upper catchment there was no participation in the planning of interventions which were based on scientific data and expert knowledge alone. Once these works were designed and funding had been obtained, volunteers were used to facilitate implementation. Volunteers had no role in decision-making and no long-term engagement was planned or carried out. Interventions were intended to be low maintenance and require little or no future intervention.

For the South Stanley Sustainable Drainage intervention our participatory community based research, which included concerns and aspirations for the proposed works (Section 2.4.3),could not be used to inform the project due to strict project scoping requirements set by the funder (see Section 5). As a result the proposal was based entirely on scientific data and expert knowledge.

In contrast, the South Moor Regeneration works included extended, formal consultation processes in their planning phases. Local residents had opportunities to comment on proposals, with views used to inform development of the final design. Consultation continued during implementation of these works and local residents developed a semi-formal co-operative arrangement with DCC staff to help facilitate interventions. This relationship has been sustained and continues to function at South Moor.

Only the development of the South Moor Heritage Trail saw deeper, less formal participation, bordering on local control. The planning and implementation of the trail was informed by a partnership between DCC and local community groups (for example walking and history groups) which collected archival data on the local area and determined the route for the circular walk. Ongoing engagement includes a community-controlled website and blog to document the development of the route and its use.

2.4.3 Opportunities for local knowledge, engagement, and participation in the Twizell Burn catchment

Results showed particular engagement with issues of flooding and drainage across the catchment, as well as land management and the amenity value of the local environment (Figure 2-4). These latter issues were often conflated as participants were predominantly interested in land management to allow greater access to the burn, for example the establishment of rights of way and access gates.

Knowledge of flooding and drainage emerged from routine local problems, such as blocked drains or highway runoff, but also included recent fluvial flood events. Participants were keen to discuss flood management, for example highlighting increases in localised surface water flooding related to new housing developments and resulting increased areas of impermeable surface. Several participants showed detailed understandings of the impact of historical development on the hydrology of the catchment, providing information on the course of historically culverted watercourses and identifying inaccuracies in GtTP mapping of the catchment extent.

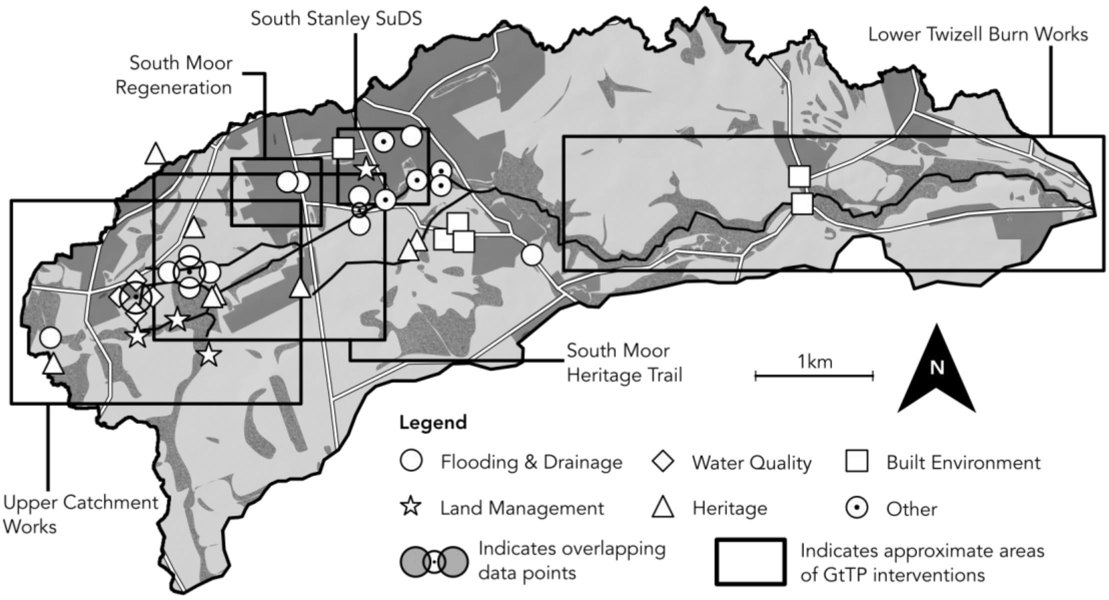


Figure 2-4. Distribution and classification of local knowledge about the Twizell Burn and its catchment collected during the participatory research. Data is displayed in point format even though some data represents knowledge distributed across an area. Boxes show the spatial relationship between local knowledge collected during the participatory research and the GtTP interventions discussed in Section 3.2.

Only a minority of participants highlighted issues of water quality or the creation of habitats. Such information predominantly related to areas of the upper catchment historically affected by minewater run-off (although this was not seen as a current problem), or sewage discharged from Combined Sewer Overflows (CSOs). These issues were noted because of their impact on the amenity value of the stream, rather than on water quality itself.

2.4.3.1 Engagement with Greening the Twizell Partnership activities

Participants reported little or no engagement with the initial consultation workshops undertaken by Groundworks for the Green Infrastructure Masterplan; although some felt they had been actively excluded. One participant expressed anger because he had attempted to contribute local knowledge of the catchment extent and drainage pathways, derived from his local knowledge, during the workshop. He felt that his knowledge had been rejected by facilitators because his information, based on an 'on the ground' knowledge of the local hydrology, conflicted with the official maps derived from national scale mapping. He felt his knowledge was dismissed because it was not 'official' and therefore could not be correct.

Almost all participants felt that no information on the GtTP, its vision for the catchment, or details of any of the proposed interventions had been communicated to them. Some participants had received information in an ad-hoc fashion through personal contacts with agency staff, but this was often fragmentary or out of date. Some participants in the upper catchment contrasted the lack of engagement with the GtTP with the historic construction of the Quaking Houses Community Wetland (Figure 3-2), a collaborative project between the Quaking Houses Environmental Trust (a disbanded local environmental group), and Newcastle University. The wetland had been constructed to treat contaminated minewater; a locally identified environmental issue (Jarvis and Younger, 1999). Whereas the Quaking Houses Wetland had been a community-led research project (Kemp and Griffiths, 1999), the lack of contact from the GtTP, particularly as some of the proposed interventions involved replacing the now derelict Quaking Houses Wetland, made them feel actively excluded from the works being undertaken.

The longer-term outcomes of the interventions were also a source of concern. Previous one-off agency interventions were dubbed 'helicopter projects', where management agencies landed to undertake capital works before taking off again. These interventions resulted in only short-term gains, unsupported by ongoing community activity. These previous projects were contrasted unfavourably with the GtTP interventions, particularly as no information was provided by the GtTP about their low-maintenance designs or their intended lifespan. As well as having limited local benefits, these interventions were perceived to exclude local people. This was because time invested by individuals was essentially wasted once the management organisations moved on. These feelings were compounded by the fact that none of the participants felt that local communities were able to take longer-term ownership of interventions.

2.5 Discussion

The results indicate that the practices of management and participation demonstrated by the GtTP were dominated by top-down, hierarchical approaches and practices typical of traditional catchment management. These findings support research by Cook (2013b) which highlighted how practices of traditional management persist due to the embedded nature of traditionally grounded policies and practices which shape emergent catchment organisations such as the GtTP.

The dominance of traditional, top-down approaches is demonstrated by the establishment of the governance arrangements for the catchment. The translation of "*The purpose of the Partnership is to be representative of stakeholders and the community* [… and to] ***work together*** *to* […] *meet the vision and objectives for the Twizell burn*" (Groundworks NE & Cumbria, 2015, p. 126) into an aim of undertaking management "*through community engagement"* (GtTP, Personal Communication) represents a significant shift from a participation-focused philosophy to one much more reminiscent of traditional management. Additionally, although "community engagement" was identified as a principle aspect of the GtTP's aim, the way in which the working practices of the partnership were operationalised acted to close down planned participatory activities. The role of local communities was limited to that of providers of information, with activities dominated by 'expert-led' practices (Fischer, 2000), and the practices of the GtTP to traditional consultation (Greening the Twizell Partnership, Personal Communication). Informing and consulting represent a low degree of power transfer in the decision making process (Figure 2-1), and formal processes are typical of traditional management (Warner, 2006).

The dominance of traditional management approaches is also demonstrated by the practices of participation evident in the interventions planned and implemented by the GtTP. Figure 2-5 maps the nature of participation demonstrated onto Plummer and FitzGibbon's (2004) multi-dimensional model of participation (Figure 2-1), and shows that interventions have a very limited local control (Plummer and FitzGibbon, 2004) at almost all stages of the planning, implementation and outcomes of each intervention. For example in the Upper Catchment Works (Figure 2-5 Nos 1, 3, and 4), participation is limited to the implementation phase with the informal use of volunteers. In contrast, the South Stanley SuDS intervention carried out by Durham County Council (Figure 2-5 No 7) was characterised by formal processes of consultation at all stages, intended to inform expert-led decision-making. Only one project, the South Moor Heritage Trail (Figure 2-5 No 9), demonstrated participatory practices and local control of both the planning and implementation stages, as well as potentially longer term participatory outcomes. This analysis also shows the advantages of using a multi-dimensional model of participation over Arnstein's (1969) relatively simplistic ladder of participation, as the original ladder would be unable to differentiate between these two practices of management, focusing instead predominantly on the outcomes which are largely the same in both cases.

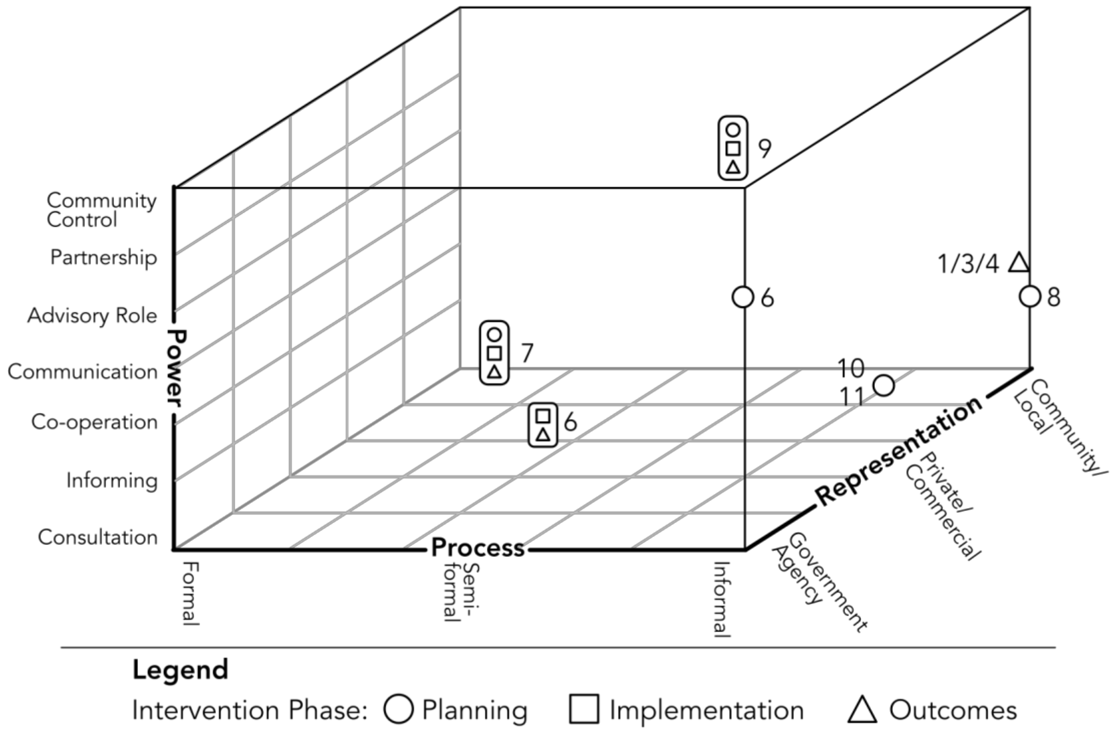


Figure 2-5. Characterising the nature of public participation in the planning, implementation, and outcomes of catchment interventions carried out by the GtTP using Plummer and FitzGibbon's (2004) conceptual model of co-operative management. Interventions mapped are (1, 3, 4) Upper Catchment Works, (6, 7) South Moor Regeneration Works, (8) South Stanley Sustainable Drainage Project, (9) South Moor Heritage Trail, (10) Fish Passage Works, and (11) Habitat Improvements. Further details of these interventions can be found in the Supplementary Information to this paper.

2.5.1 Vertical integration in the practices of management of the GtTP

The driving top-down policy, CaBA, uses the sub-catchment as the key scale for the implementation of community-led, participatory activities. However research findings from our community-focused research and activities to develop the Green Infrastructure Masterplan demonstrate that these aspirations are not delivered. This bottom-up research indicated a broad understanding and engagement with the catchment of the Twizell Burn from local communities. An emergent aspiration for participation and local control related to a range of issues which extended widely beyond the relatively narrow focus of the GtTP was also evident.

We explain this apparent disjuncture between policy, emergent aspirations for participation, and the practices of participation demonstrated by the GtTP by exploring the vertical interplay between the drivers of management and participation occurring at different scales within the management process (Watson, 2014; Young, 2006). Young (2006) argues that vertical interplays are interactions between management systems occurring at different scales; in this case the local, catchment, and supra-catchment scales (Figure 2-2). These management systems have different policy instruments, systems, and associated behaviours (Watson, 2014). Contrasting systems at different scales can result in differing outcomes depending upon the relationship between the scales. Young (2006) proposed five potential modes of interaction characterised by their degree of integration, ranging from the dominance of a higher level system through to the integration of two systems resulting in systemic change.

Figure 2-6 maps four of the interventions undertaken by the GtTP against Young's conceptual model, exploring drivers and principle actors at each scale to illustrate the vertical interplays in each case. Interventions (a-c) represent the majority of the interventions carried out by the GtTP, whilst (d) shows the South Moor Heritage Trail; the only intervention to achieve meaningful local participation. Results indicate that the routine practices of the GtTP are characterised by a dominant vertical interplay (Young, 2006), with participation at the local level dominated by supra-catchment drivers. Two principal sources of drivers are apparent depending on the focus of interventions. For WRT-led projects (Figure 2-6a and b), the WFD acts as the driver, establishing top-down objectives for the achievement of minimum water quality standards for the Twizell Burn (Voulvoulis *et al.*, 2017). These supra-catchment objectives are translated to the local level through the provision of project funding, provided in this case by the Catchment Partnership Action Fund (CPAF) (Defra, 2016). This funding is heavily controlled and provided only to projects targeted at WFD compliance. It provides funds for immediate capital expenditure and not for ongoing maintenance or engagement work. Use of this funding source forced WRT to maintain tight control of the planning and implementation of these interventions (Cook *et al.*, 2013b; Mees *et al.*, 2017) since the inclusion of unfocused local aspirations represented a significant barrier to obtaining the funding. Hence WRT was unable to use the data collected during the South Stanley SuDs project as, although the data highlighted the potential for a wide-ranging, locally controlled project with multiple benefits, this was not achievable through CPAF funding. Instead, WRT was forced to adopt a model of participation that, following Plummer and FitzGibbon's (2004) model (Figure 2-5 No 8), undertook engagement as an informal process with very limited representation, with only those who could contribute relevant knowledge, skills, or labour asked to participate, and no transfer of decision-making power. The lack of long-term involvement by WRT in these interventions, dictated by the use of CPAF funding, meant that there was no potential for these limited participatory practices to develop into anything further (Schild, 2018).

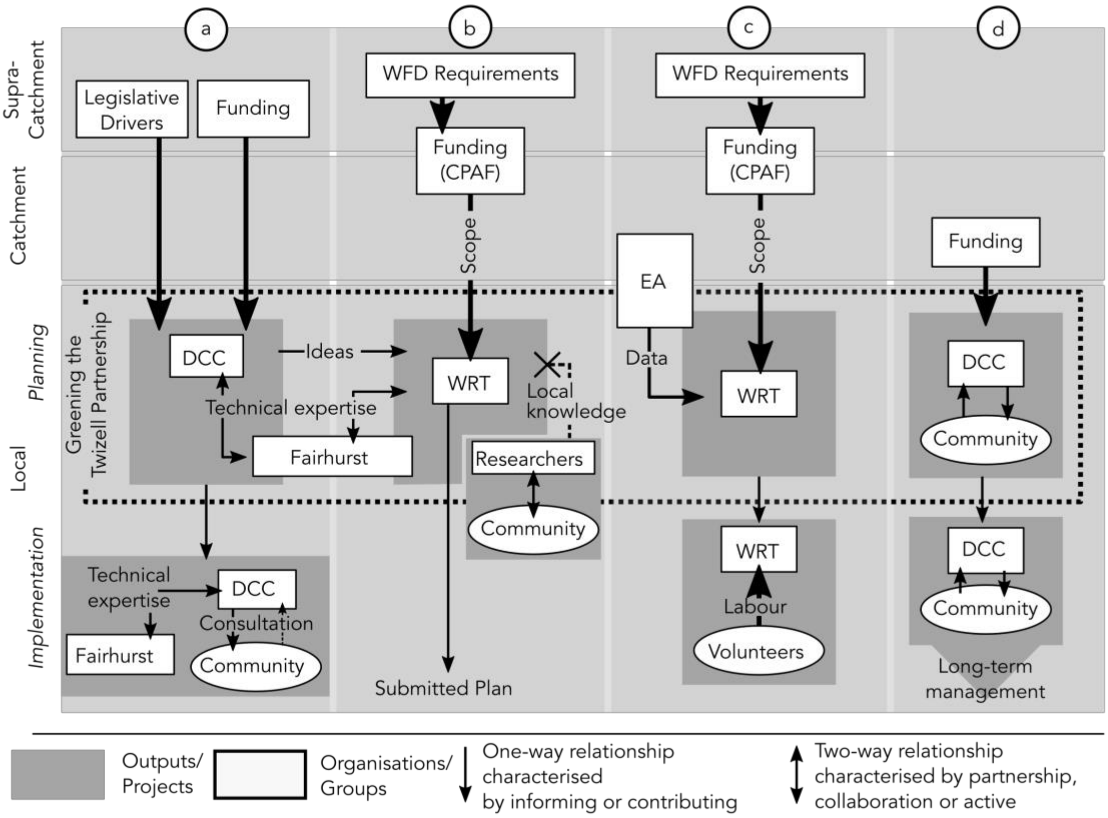


Figure 2-6. Mapping the vertical interplay between drivers and actors at different scales within the management process in the Twizell Burn. Interventions mapped are (a) South Moor Regeneration Works, (b) South Stanley Sustainable Drainage Project, (c) Upper Catchment Works, and (d) South Moor Heritage Trail. The actors referred to within the figure represent the main agencies within the GtTP discussed in Section 2.3.

For DCC-led urban regeneration projects (Figure 2-6a), supra-catchment legislation, including the Planning Act 2008 and Localism Act 2011, dictates how the council, as spatial planning authority, must function (Landmark Chambers, 2014; Ministry of

Housing, Communities & Local Government, 2017). This legislation is grounded in traditional approaches to consultation, with mandated formal practices to demonstrate due process in the event of planning disputes (Blowers, 2017). Evidence of these approaches are seen in the formal practices adopted during the South Moor Regeneration Works, with only a low transfer of power through formal processes, although representation is widespread within the local area (Plummer and FitzGibbon, 2004). Participation is once again a barrier to achieving interventions, albeit different to that experienced by WRT. Delivery of statutory duties means DCC practices are not aligned with deeper community participation, resulting in a practical barrier in terms of limited time and resources (Cook *et al.*, 2012). The subsequent development of a semi-formal, co-operative relationship between DCC staff and local residents demonstrates the benefits of participation and the willingness of DCC staff to adopt a more flexible approach to participation when it is clearly beneficial to their interventions.

The only project with a deeper participation and local control was the South Moor Heritage Trail since the vertical interplay is not dominated by supra-catchment drivers with top-down objectives (Figure 2-6d). Local participation here was not a barrier, but a driver. The project was therefore able to develop a participatory model closer to the collaborative ideals of ICM (Marshall *et al.*, 2010), with high levels of local representation through an informal and ongoing process and the dispersion of decision-making power to local groups; both in the planning and long-term management of the intervention.

2.5.2 Horizontal integration in management practices

Whilst the results indicate limited success in achieving vertical integration, they demonstrate the emergence of a successful form of collaborative, horizontally integrated management between members of the GtTP (Varis *et al.*, 2014). Projects, regardless of their supra-catchment drivers were all funnelled through the GtTP (Figure 2-6) which enabled the group to act as a collaborative forum in which a degree of social learning (Allen *et al.*, 2011; Collins and Ison, 2009), along with development of shared goals could be achieved between representatives of traditionally discrete agencies. This is evidenced through the development of the original Green Infrastructure Masterplan, which envisioned a systems-based approach to the management of the Twizell Burn and the development of a range of interventions targeting ecological and socio-ecological systems. Collaboration between different agencies in the sharing of ideas, expertise and data occurred (Margerum, 1999), for example the use of DCC project data arising from the South Moor Surface Water Management Plan used to inform the South Stanley SuDS project (Figure 2-6a and b). However, this collaboration was limited and based mainly on personal relationships developed between specific individuals within the GtTP, including long-standing professional relationships. One aspect where collaboration was unable to achieve more effective systems working and better vertical integration, is in breaking out of the path dependency (Kirk *et al.*, 2007) dictated to each agency by its supra-catchment drivers. This reflects the fact that social learning was undertaken on an individual level between specific members of the GtTP, and was not representative of wider institutional processes of social learning. More 'official' processes, or deeper relationships between individuals from professional organisations would be necessary for the agencies represented within the GtTP to break out of their traditional management paths. However, the development of these collaborative forms of working offers hope that further development of these relationships might facilitate more diverse working practices. Agencies would also be able to call on a wider suite of funding sources (Cook *et al.*, 2013b), thereby reducing the dominant vertical interplay evidenced by this research. Reducing the dominance of supra-catchment drivers on local practices would remove the barrier of participation demonstrated here. The emergence of bottom-up aspirations for participation would be an asset to planning, delivering, and maintaining locally relevant and integrated management interventions.

2.6 Conclusions and recommendations

Catchment management has been ostensibly revolutionised by the participatory principles of ICM. Policies mandating citizen participation in planning and decision-making are now widespread, for example the Water Framework Directive, with the management system conceptualised by nested cycles of partnership working (Figure 2-2). However, nearly twenty years after the WFD was implemented across the EU widespread research has shown that catchment management at the local, sub-catchment scale remains dominated by traditional, top-down approaches which exclude local communities from any meaningful participation in catchment management. These practices result from a dominant vertical interplay between supra-catchment drivers and local practices which restricts vertical integration between agencies and communities within the catchment. Participation is limited in either power transfer and/or representation (Figure 2-5) by the tightly controlled scope of catchment interventions, designed to meet strict funding criteria set at the supra-catchment level, or by the processes used by statutory bodies for formal consultation, again dictated from the supra-catchment level.

Hence despite a policy aspiration for integrating bottom-up participation into catchment management, emergent participatory movements, such as that shown in the Twizell Burn, which are characterised by multiple and complex knowledges and aspirations for management activities, remain obstacles to achieving supra-catchment objectives. Only where these supra-catchment drivers were absent did deeper participatory practices emerge.

The results presented here show the emergence of a greater degree of horizontal integration between agencies, allowing traditionally distinct sectors of management activity to be brought together. By working more closely together, opportunities to exploit or share new funding sources outside of their traditional domains may be opened up, potentially enabling time and flexibility for greater vertical integration to emerge. Although this is positive, catchment groups in other areas must navigate different vertical interplays depending on their local circumstances, and therefore emergent horizontal integration cannot be relied upon to drive vertical integration and the meaningful integration of communities into environmental decision-making.

Instead of acting as a barrier to implementing management, local knowledge and participatory aspirations should be an opportunity to develop effective and locally driven management practices. Further work is necessary to move participatory activities away from the low-power-low-representation or low-power-formal-process models demonstrated in this research, in particular:

1. The supra-catchment governance structures which currently control catchment management at the local scale must be challenged and restructured. Meaningful participation within ICM requires time, to establish informal, trusting relationships with local communities, and flexibility of process, to work together with emerging participatory movements. Future practice and research in ICM should explore how local-level governance structures can be established, to diversify practices of management, reduce the influence of the supra-catchment drivers, and revive meaningful localism.
2. The ways in which participatory governance of local environmental issues might be undertaken should be examined to demonstrate how management organisations can enhance their work through meaningful vertical integration. The policies and practices of traditional governance exclude local knowledges as 'unscientific' and incompatible with the scientific, expert-driven management practices (Eden, 1996). However, research has long challenged this view (Wynne, 1996).
3. To support the establishment of more participatory catchment governance structures, research should demonstrate: (i) how the credibility of different information sources can be assessed; (ii) how alternative knowledges can be used within existing frameworks of knowledge creation to inform decision-making; and (iii) how new mechanisms for social learning and shared decision-making can be established to implement the renewed localism needed in ICM practice.

Supra-catchment policies such as the WFD have fundamentally altered how catchments are managed, attempting to encourage the bottom-up management of catchments through participatory practices. However, this research has demonstrated, nearly twenty years after the WFD came into force, the difficulties of changing embedded practices of management dictated by a complex and interlocking array of drivers operating on different actors and at different scales within the management cycle. Only by addressing both policy and governance at the supra-catchment level, to encourage flexibility and self-determination at the local level, and developing tools and practices, to bring together alternative knowledges and perspectives, can this disparity be overcome and the participatory culture of ICM be embedded within catchment management practice.

Chapter 3 The importance of volunteered geographic information for the validation of flood inundation models

Overview: This paper presents a method for improving the validation of two-dimensional flood inundation models using community collected Volunteered Geographic Information. The method builds on traditional statistical validation methods by using non-traditional data, collected during and immediately after a flooding event, to validate the pathways, timings, and impacts of the flood both spatially and temporally. The application of the method to a test site in the northeast of England shows the effectiveness of using non-traditional data in assessing the validity of the model's simulation of spatial and temporal floodplain inundation.

Motivation: Based on the findings of the research undertaken in the Twizell Burn, Chapter 2 recommended the exploration of alternative methods for integrating alternative knowledges into existing practices of scientific knowledge creation and decision-making. The purpose of this paper was to address this issue by demonstrating how local knowledge and perspectives could be integrated into Flood Inundation Modelling. Flood Inundation Modelling is a critical aspect of flood risk management which is typically dominated by traditionally regarded scientific knowledge and expert analysis. The proposed validation framework provides a potential role for at-risk communities as active participants in flood inundation modelling.

Citation information: This chapter was published in the Journal of Hydrology as E. Rollason, L.J. Bracken, R.J. Hardy, A.R.G. Large, The importance of volunteered geographic information for the validation of flood inundation models, Journal of Hydrology, Available online 4 May 2018, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2018.05.002.

Author Contributions: In this paper, I designed the research methodology, operationalised the LISFLOOD-FP model, undertook the empirical data collection, wrote the text, created the figures and led the paper development. My co-authors provided editorial input and guidance on the development of the paper.

3.1 Introduction

Flooding is one of the most serious environmental hazards globally, with flooding the cause of almost 50% of all economic losses resulting from natural hazards (Munich Re, 2013); and losses are likely to increase under climate change as flooding is exacerbated (Hirabayashi et al., 2013; Reynard et al., 2017). The need to better understand current and future flood risks has led to a significant rise in the use of predictive numeric models to understand river processes, including flooding (Bates and De Roo, 2000; Hunter et al., 2007; Lane et al., 2011a; Parkes et al., 2013). The availability of high quality, spatially-distributed data on river environments (Cobby et al., 2003) means two dimensional models, capable of explicitly simulating complex, spatially and temporally-differentiated floodplain flows are now a standard approach in many fields, including the insurance industry (Bates and De Roo, 2000; Bradbrook et al., 2004; Hunter et al., 2007; Néelz and Pender, 2013; Teng et al., 2017). However, improvements in data, and advances in numerical modelling techniques, have not been matched by improvements in the validation of these models; the process by which we can assess whether our models agree with observations (Refsgaard and Henriksen, 2004). Established approaches to validation are typically spatially or temporally limited in scope by the availability of accurate datasets.

This paper seeks to address gaps in our existing data and practices of model validation. Using a case study from northeast England, we propose a new approach, which builds on existing statistical methods of comparison against observed data. We demonstrate that, by exploiting diverse, volunteered and crowd-sourced datasets, we can both spatially and temporally reconstruct the key dynamics of flood events. The approach demonstrates how alternative data-sources can be used to enhance existing data, providing information on flooding processes for which traditionally regarded data is rarely available. Finally, the approach offers a more holistic validation of the complex dynamics of floodplain flows, including the pathways, timeline, and impacts of events.

3.2 Application of Volunteered Geographic Information in Hazard Assessment

3.2.1 VGI data in Disaster Risk Reduction

Paucity of measured data on disasters, including floods, is common in the field of Disaster Risk Reduction (DRR). To address this issue, research has explored the use of non-standard, unscientific datasets derived from local communities within a disaster zone (Goodchild and Glennon, 2010). One data source being explored within DRR research is Volunteered Geographic Data (VGI: (Haklay et al., 2014)), defined as 'the widespread engagement of large numbers of private citizens, often with little in the way of formal qualifications, in the creation of geographic information' (Goodchild, 2007, p. 212). VGI datasets include any geo-located information on a disaster, and can comprise a diverse range of data including personal accounts, photographs and videos, and crowd-sourced measurements (Hung et al., 2016; McDougall, 2012; Triglav-Cekada and Radovan, 2013).

The use of VGI datasets has been demonstrated across a wide range of studies of hazard events (for systematic reviews of the current research base see Granell and Ostermann, 2016; and Klonner *et al.*, 2016). For floods, the use of VGI data has been demonstrated across a range of applications. For instance, McCallum *et al.* (2016) utilised VGI to improve the availability of pre-event data on flood vulnerability in data-sparse regions, demonstrating how crowd-sourced information can enhance mapping for emergency responders after disasters. A number of studies have also explored the potential for collecting VGI datasets to inform real-time disaster response. For example, Wan *et al.* (2014) at a global scale, and Degrossi *et al.* (2014) and Horita *et al.* (2015), both working at city scale in Brazil, demonstrated cloud-based systems for the collection and processing of VGI flooding data. These systems synthesised diverse flooding datasets, providing real-time information for emergency response and developed a long-term database of information on historic floods. VGI has also been used in the post-event phase: Schnebele and Cervone (2013) and Triglav-Cekada and Radovan (2013) utilised VGI flooding imagery collected after the event to improve flood maps derived from satellite imagery. Such research demonstrates how the VGI data can provide spatially distributed information on even large flood events, and how it can also be used to validate remotely-sensed hazard maps at a local scale.

While these examples demonstrate the emerging, widespread application of VGI for disaster preparedness and response, they also demonstrate how limited and fragmented the use of VGI data is for many applications; reflecting the non-standard nature of the data. McCallum *et al.* (2016) use only participatory mapping for their vulnerability assessment, whilst Schnebele and Cervone (2013) and Triglav-Cekada and Radovan (2013) use only imagery for their flood mapping analysis. Wan *et al.* (2014), Degrossi *et al.* (2014), and Horita *et al.* (2015) collected a wider range of data, including citizen reports of flooding, but highlighted significant problems utilising such diverse datasets which cannot be automatically processed. Other criticisms of VGI datasets often focus on issues of data validity or the difficulties of assessing data quality in the absence of traditionally-measured data sources (Hung et al., 2016; Muller et al., 2015). As a result, many studies use collection of VGI data as an adjunct to traditional data, rather than as a source of data in its own right or as a standalone method for the creation of new knowledge about specific hazards such as flooding (Usón et al., 2016).

3.2.2 Emerging practices of engagement

In contrast to the VGI projects noted in section 3.2.1, citizen science and citizen observatory programmes represent moves towards establishing new practices of geo-spatial knowledge co-creation. These efforts are driven by the need for greater public participation in environmental decision-making (National Research Council, 2008) laid out in the Aarhus Convention (Lee and Abbot, 2003) and the European Floods Directive (Wehn et al., 2015). Citizen science and citizen observatories have been demonstrated across a range of disciplines including flooding and hydrology

(Lanfranchi et al., 2014; Muller et al., 2015; Ruiz-Mallén et al., 2016; Starkey et al., 2017), and research has begun to demonstrate how citizen-led, locally collected data can provide valuable information for enhancing our understanding of catchment processes and planning catchment interventions (Starkey et al., 2017). In contrast to the often *ad-hoc* collection of VGI data, citizen science typically involves engaged and trained participants and rigid data collection frameworks to help overcome issues of data validity (Wiggins and He, 2016).

However, an issues arises: flood events, in common with other disasters, represent situations in which data can often only be collected in an *ad-hoc* fashion, as the presence of local volunteers able and willing to collect data cannot be guaranteed (Starkey et al., 2017). This is particularly relevant as citizen science programmes are often limited to small numbers of participants (Baruch et al., 2016), meaning drop-outs during an event would have a greater impact on the data collected. Efforts therefore need to be made to understand how we can integrate the opportunities for large scale engagement represented by VGI with the opportunities for local participation, and the improvements in data quality, represented by citizen science. Studies have begun to explore how integrating citizens into activities beyond simple data collection can improve engagement and data quality, for example see Starkey *et al.* (2017), but in the context of flooding this field is still in its infancy. However, there is obvious potential for a more integrated approach between large scale VGI data collection and the more locally focused nature of citizen science (for a review of the present state of citizen science and VGI research see Brandeis and Carrera Zamanillo, 2017 for further details).

3.2.3 Integrating citizen data into the validation of flood inundation models

One situation which potentially offers the opportunity to integrate citizen science and VGI in this way is in the construction and validation of numerical flood inundation models of flood-affected communities. Flood inundation modelling forms a cornerstone of flood risk assessment (Bates and De Roo, 2000; Hunter et al., 2007; Lane et al., 2011a; Parkes et al., 2013). It informs almost all flood management activities, from monitoring and warning systems (Nester et al., 2016), to evacuation planning (Simonovic and Ahmad, 2005) and emergency response (Coles et al., 2017), to the design and construction of future developments (Pappenberger et al., 2007a). However, at present, flood modelling is primarily an expert-led activity with little or no citizen involvement (Lane et al., 2011b).

The established approach to validating inundation model outputs is to match available historical data to simulated outputs (Pappenberger et al., 2007a). The goodness-of-fit between predicted and observed river levels can be assessed using statistical best-fit techniques such as Nash-Sutcliffe Model Efficiency (NSME) (Nash and Sutcliffe, 1970) or Root Mean Square Error (RMSE) (Altenau et al., 2017). Similarly, point-in-time global flood extents can also be assessed using binary performance measures such as the Critical Success Index (C), which compares the extent of simulated inundation to the observed inundation (Wing et al., 2017). What tests are undertaken is dependent upon data availability. In-channel river level data is a source of historical information commonly available in medium and large catchments (Hunter et al., 2007; Parkes et al., 2013). To examine out of bank inundation, high resolution aerial and satellite imagery (Renschler and Wang, 2017), multiband remote sensing such as LANDSAT (Fernández et al., 2016; Jung et al., 2014), or other sensors such as Synthetic Aperture Radar (García-Pintado et al., 2013; Pappenberger et al., 2007b; Wood et al., 2016) can all be used. Studies have also demonstrated the usefulness of ground observations of wrack and water marks in reconstructing maximum inundation extents and levels, (Neal et al., 2009; Parkes et al., 2013; Segura-Beltrán et al., 2016). However, collection of this latter form of flood inundation evidence typically requires post-event surveys which are time and resource consuming and often yield spatially limited results (Segura-Beltrán et al., 2016).

The validation of model outputs is therefore constrained by data availability to being either spatially or temporally limited: gauged river levels may record levels throughout an event but are limited to discrete locations; whilst remote sensing can provide spatially extensive information on inundation but only at discrete time points. Consequently, established statistical techniques for model validation have been unable to assess the effectiveness of models in simulating both spatial **and** temporal event dynamics (Hunter et al., 2007). These dynamics include the pathways which water takes across the floodplain, the flood timeline, and local variation in flood impacts; all of which are capable of being simulated in detail by current 2D inundation models (Teng et al., 2017). This disparity between the complexity of current inundation models and the relative lack of data against which to test them represents an opportunity to integrate citizen-collected data into existing, expert-led practices of knowledge creation. Thus far however, there has been little exploration of this issue.

3.3 Methods

In this research we build on the methodology used by Smith *et al.* (2012) by demonstrating how VGI data should be used more routinely for model validation as a dataset in its own right. Smith *et al.* (2012) provide a demonstration of the use of a diverse VGI database to construct and validate a model of coastal flood defence overtopping. They utilise VGI to build the model, by using locally recorded locations of flood defence overtopping as point inflows into the model domain. They also validate its outputs, reconstructing the observed flood extents and depths at properties using historical photographs and media accounts. However, the approach demonstrated was limited by the data used, which was confined to imagery and records of depth at specific locations. By examining only modelled extent and depth, the method provides a spatial but not a temporal validation. The resultant validation cannot examine the functioning of the model in simulating flood dynamics in more detail, nor does the study explore how VGI could be used more comprehensively. This is reflected in Smith *et al.*'s conclusion that the data used represented "*useful* ***corroborating*** *evidence for the performance of the model"* (p. 43), after a more traditional validation using available measured data.

In this study we develop an experimental validation methodology which uses a wide range of data potentially available through VGI and participatory research approaches to examine different aspects of a simulation output. To demonstrate the method we use a database of VGI to reconstruct in detail a severe flood in the northeast of England, and use a VGI-based flood reconstruction to validate the outputs of a 2D flood inundation model of the event. Finally, we compare the outputs to more established methods of validation to demonstrate the success of the method.

3.3.1 Model Build

We utilised the flood inundation model LISFLOOD-FP to produce simulated flood event outputs for our case study. LISFLOOD-FP is a 2D finite difference model developed specifically to utilise high resolution topographic data to simulate floodplain dynamics (Bates et al., 2010; Hunter et al., 2005; Neal et al., 2012, 2011; Bates and De Roo, 2000). Although we used LISFLOOD-FP here, the validation approach developed should be considered generic, and is designed to be applicable to any 2D model that predicts dynamic floodplain inundation. The principle data requirements for the model are outlined in Table 3-1.

Table 3-1. The principle data requirements of the LISFLOOD-FP model and the data used in the construction of a model for this study.

Model Component	Data Required	Data Used in the study
Topography	Pre-processed, 'bare-earth' raster grid of topography with buildings and vegetation removed	Environment Agency 2m horizontal resolution 'bare earth' LiDAR data, resampled using averaging technique Structures, e.g. bridges and flood defences, added to the DEM prior to inclusion in the model
Inflow conditions	Stage or discharge inflows	Point inflows from Environment Agency gauging stations at 15 minute temporal resolution

Model Component	Data Required	Data Used in the study
Outflow conditions	A downstream boundary derived from either gauged river levels or a free flow boundary	Free flow boundary using slope calculated from local DEM values
Floodplain friction parameters	A raster grid representing Manning's 'n' values for different landcover classes	Values estimated from Chow (1959) based on satellite imagery and field visits

3.3.1.1 The case study: The 2015 Corbridge flood

The test case used in this study is the market town of Corbridge, located in the Tyne Valley in the northeast of England (Figure 3-1). Corbridge was chosen to develop and test the experimental validation because of its recent history of severe flooding and the way its population were already engaged with ongoing flood research (Rollason et al., 2018).

Corbridge has a long history of flooding, with records dating back to the 1700s (Archer et al., 2007a). Most the town is situated on a terrace to the north of the river, at least 15m above the floodplain. However, the areas of Station Road and the Stanners (Figure 3-1) are vulnerable to flooding as they are located on the floodplain south of the river. This area includes approximately 70 properties, both residential and commercial. Corbridge had been affected by flooding most recently in 1995 and 2005; with recorded water levels at the Corbridge gauge of 28.01 m, and 28.58 m respectively, with the 2005 flood estimated to have a return period of 71 years (Archer et al., 2007a). In 2005 flooding had occurred partially as a result of the failure of flood defences (Archer et al., 2007b), with the flood defence embankment upstream of the bridge, which was in the process of being repaired, collapsing. Following this flooding event the bank as repaired and strengthened, and the wall downstream of the bridge was also raised.

Corbridge experienced extensive flooding when Storm Desmond resulted in record rainfall across areas of the north of England (Barker et al., 2016) on 5th December 2015. The flood, an event with a return period estimated to be between 100 and 200 years (Marsh et al., 2016), overtopped the flood defences at Corbridge, and inundated the 70 properties on the south side of the River Tyne (Environment Agency, 2016).

Using LISFLOOD-FP a model of the River Tyne was constructed, extending for approximately 30km, with Corbridge situated approximately half way down the modelled reach. Figure 3-1 shows the modelled reach and the main data used are discussed in Table 3-1. To predict the December 2015 flood event, the model was run for a 72 hour period starting at 12:00 on Friday 4th December continuing until 12:00 on Monday 7th December. This period covered both the rising and falling limbs of the main hydrograph at Corbridge. Simulation results were generated for every 15 minutes period, predicting flood depths, flood velocity, and time of inundation.

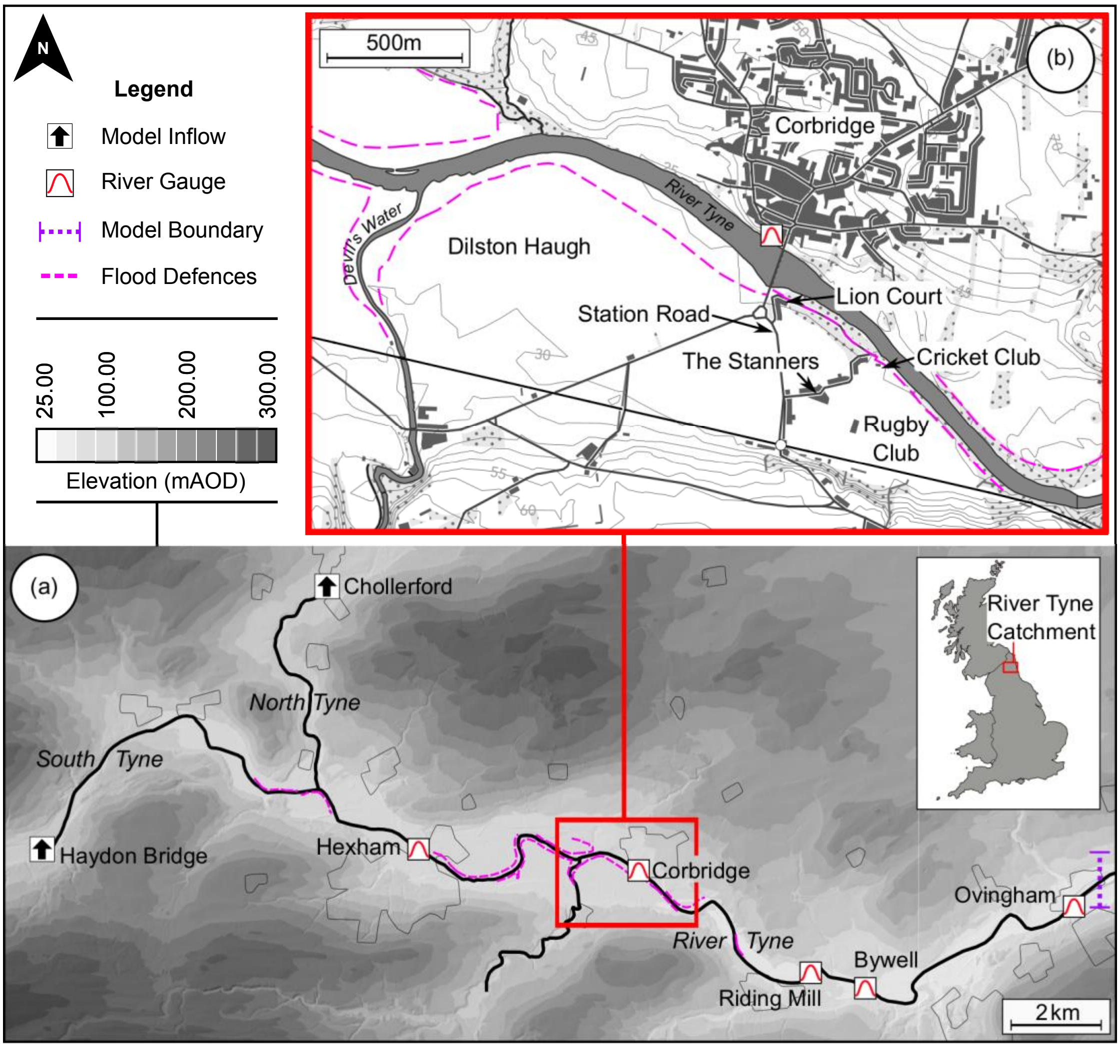


Figure 3-1. (a) The modelled reach showing the key elements of the model and the locations of the boundary conditions used. (b) The Corbridge study area and locations referred to in the text.

3.3.2 Validating the model outputs using established approaches

Initial verification and calibration of the model was undertaken during the model build. The mesh resolution independence of the model was verified by testing against DEM resolutions of 5.0, 7.5, 10.0, and 20.0 metres (Hardy et al., 1999; Horritt and Bates, 2001). The model was further calibrated against floodplain friction values, which were estimated from Chow (1959) based on satellite imagery and field visits. Differential friction values were applied to the channel of the Tyne and the main floodplain, with the area of the channel delineated based on satellite imagery. Manning's values for floodplain friction between 0.02 and 0.06 ($m^{1/3}\ s^{-1}$) and channel friction values between 0.03 and 0.07 ($m^{1/3}\ s^{-1}$) were used in the model calibration runs, validation of which was undertaken using established statistical approaches. Validation was also undertaken on the calibrated model as a baseline against which to test the effectiveness of the experimental methodology.

Two datasets were available for the validation using established statistical techniques: gauged river levels and observed flood extents for the estimated maximum extent. Gauged river levels were validated using both Nash-Sutcliffe Model Efficiency (NSME) and Root Mean Square Error (RMSE) (Altenau et al., 2017). Maximum flood extents were validated using the Critical Success Index (*C*) (Wing et al., 2017; Wood et al., 2016), sometimes referred to as the 'fit statistic' (Sampson et al., 2015). *C* tests the proportion of wet observed data that is replicated by the model on a per-pixel basis, accounting for both over- and under-prediction:

$$C = \frac{\mathrm{M_1O_1}}{\mathrm{M_1O_1} + \mathrm{M_0O_1} + \mathrm{M_1O_0}}$$

Where M is the modelled outcome and O is the observed outcome, and 1 or 0 represents pixels that are either wet or dry. *C* can range from 0 (no match between simulated and observed inundation) to 1 (perfect match between simulated and observed inundation).

3.3.3 Developing a new solution for validating inundation models

3.3.3.1 The Volunteered Geographic Information Database

Participatory research in Corbridge was undertaken with the community to develop a VGI database of local knowledge and experiences of the December 2015 flooding event. As part of wider participatory work being undertaken at Corbridge (for further details see Rollason et al., 2018) we carried out two participatory mapping workshops with 10 research participants, and five individual walking interviews, after Evans and Jones (2011). Discussions and interviews were un- or semi-structured in nature (Dowling et al., 2016), with participants being encouraged to lead the discussion and discuss their own knowledge and experiences. During the mapping workshops participants were encouraged to locate their knowledge on blank maps of the study area, for example observed locations of defence overtopping or pathways of flood water flow. Walking interviews were also participant-led following either the natural go-along (Kusenbach, 2003), or participatory walking interview (Clark and Emmel, 2008) models. Spatial data were recorded either directly into GIS or onto paper maps for later digitisation. Verbal discussions were recorded and analysed by adopting a grounded theory approach (Charmaz, 2011), combining both the audio recording and visual representations (Knigge and Cope, 2006). Information provided in anecdotal accounts was triangulated with digital images and video taken during the event and collected during the participatory process.

The information were used to produce an extensive database of how the flood occurred (Table 3-2). Most of the data was collected from the local community but it was augmented by (non-georeferenced) footage from an unmanned aerial vehicle (UAV) identified on news footage immediately after the event, and collected by a local UAV enthusiast.

Table 3-2 VGI data used for reconstruction of the December 2015 flood event. Data was collected between April and May 2016.

Data Type	Source	Quantity
Personal accounts	• Interviews and correspondence with individual members of the Corbridge Flood Action Group	5
Mapped data	• Group mapping workshops undertaken with members of the Corbridge Flood Action Group	Outputs from two group mapping workshops
Photographs	• Photographs taken during or immediately after the flooding event showing flood pathways or impacts, e.g. areas of gravel deposition or wrack lines, contributed by members of the Corbridge Flood Action Group • Photographs taken after the event by the researchers showing impacts e.g. wrack lines	18

Data Type	Source	Quantity
Video	• Videos taken during the flood event by members of the Corbridge Flood Action Group	2
	• Videos taken by UAV immediately after the flooding event and obtained through correspondence with research participants.	2 – one taken 24hrs after the peak of the flood and one 48hrs after the peak of the flood

3.3.3.2 Using the VGI database to reconstruct the dynamics of a severe flood

During validation it is necessary to establish the main dynamics of the flooding event for which the model is being validated. To do this, we divided the VGI data into three information categories:

1. **Pathways** – data which provided information on the movement of flood water through the study area, including areas of overtopping and principle flow directions.
2. **Impacts** – data which provided information on the maximum extent of the flooding.
3. **Timeline** – data which provided information on the timing of key events during the flood, including overtopping of defences, arrival of flood water at key locations, and inundation of properties.

Mapped data and personal accounts (anecdotal data) were combined into a single vector layer within a GIS, with the anecdotal data included within the layer as specific or linked attribute data following the qualitative GIS approaches of Cope and Ellwood (2009). This layer was used to reconstruct a unified account of the event dynamics, including times of overtopping and inundation of properties. Photographs and videos were georeferenced and quantitative information was extracted where possible, for example the location of wrack or height of flood marks, or the direction of gravel deposition showing flow pathways. Where quantitative data was not collected directly, images were used simply for interpretation and to validate other data sources. Perks *et al.* (2016) have demonstrated how georeferenced UAV data can allow precise quantification of flood flows and flow vectors for an urban situation in Scotland. However, the UAV footage collected during the Corbridge study was obtained opportunistically and as a result did not contain the necessary metadata or ground control point information to allow it to be georeferenced. It was thus used in an analytical manner: using darker surface colours or isolated water bodies to indicate previous areas of inundation (Renschler and Wang, 2017). In areas where no footage was available, interpolation of the flood extent was undertaken based on expert judgement and using LiDAR topography.

3.3.3.3 Quality control of VGI data

The VGI dataset collected for this study is fragmentary and 'format-messy'. This makes the assessment of data quality using traditional quantitative measures difficult. However, it is still necessary to assess the extent to which we can have confidence in the data and the flood event reconstruction derived from it and, to do this, we adopted the approach of Mays and Pope (2000). This validation approach uses a researcher-led, reflexive approach relying on triangulation of different data sources to assess and validate individual pieces of information; for example the comparison of anecdotal accounts with imagery or physical evidence on the ground. This approach does not provide the quantifiable analysis of error normally required for model validation. Instead, the method identifies areas of error and uncertainty (spatial and temporal), or contested knowledge which can arise due to the nature of the VGI data being used.

3.3.3.4 The experimental framework for model validation

The experimental validation brought together the flood event reconstruction derived from the VGI database with the outputs of the LISFLOOD-FP model which represent the dynamics of the event. The outputs showed dynamic flood depths and flow vectors, times of inundation, and maximum flood extents.

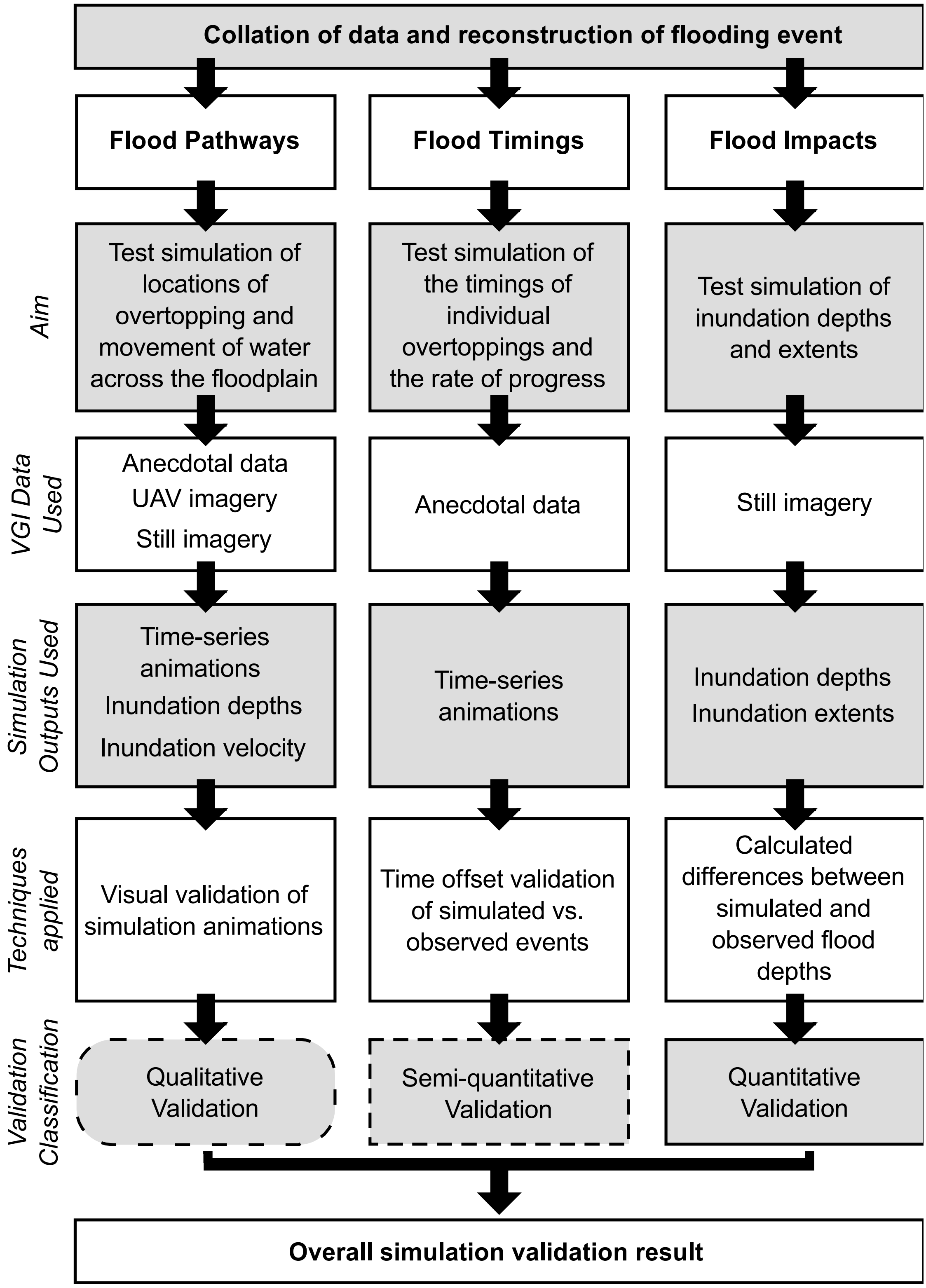


Figure 3-2. The experimental approach showing the types of validation which can be applied, depending on the available information and how these correspond to the dynamics of the event. The availability of data and the validation methods adopted influences the nature of the final validation, which represents a blend of qualitative, semi-quantitative, and quantitative data and methods.

Flood depths and times of inundation were extracted directly from the model at user-defined time-steps in raster grid format. As a velocity output, the model produces grids representing the flow of water between grid cells in both the x and y directions. To convert these velocity grids into flow vectors, the SAGA GIS tool 'Gradient Vectors from Directional Components' (Conrad et al., 2015) was used. An average across 4 grid cells (40m) was used to reveal underlying flow directions which could be compared against the observed evidence.

Figure 3-2 shows the experimental approach and the VGI datasets used to validate the different dynamics of the event.

3.4 Results

3.4.1 Calibration and validation of the model outputs using established methods

Table 3-3 shows that the model performed consistently well in simulating gauged water levels along the whole modelled reach with a floodplain Manning's *n* of between 0.03 and 0.07 ($m^{1/3} s^{-1}$) and a DEM resolution of either 10 or 20m. This DEM resolution is in line with the recommendations of the UK Environment Agency Fluvial Design Guide (Crower, 2009), which suggests model resolutions of 25m in rural areas and 10m for urban areas. It is also in line with other catchment or sub-regional studies, although there is significant variation in the resolutions used (Gobeyn et al., 2017; Neal et al., 2011; Renschler and Wang, 2017; Savage et al., 2016; Wing et al., 2017). Some studies have demonstrated the use of very high resolution topographic information, for example Sampson *et al.* (2012), but these are exclusively applied to small scale, urban studies rather than the larger, rural reaches such as that simulated in the current study.

Table 3-3 also indicates the goodness of fit, measured by the Critical Success Index *C*, between the simulated and observed maximum flood extents within the study area. The results indicate that all of the tested parameter sets achieved greater than 85% success in matching the observed peak flood extents. The calibrated model achieved a 90% success rate, which compares very favourably with other modelling studies which achieved between 50% and 90% success rates (Renschler and Wang, 2017;

Wing et al., 2017). At a local scale, visual assessment of the simulated and observed extents (Figure 3-3) show that within the area of interest there was considerable variability in areas of over- and underestimation. In particular, the model overestimated the extent of overtopping of the flood defences at Dilston Haugh (Figure 3-3 location a) and at the Rugby Club (Figure 3-3 location b), whilst it underestimated the extent of flooding on Dilston Haugh. It is considered likely that the bare earth DEM (vegetation and buildings removed) used in the model contained inaccuracies which influenced the flow of water across the floodplain, which will be discussed further below.

Table 3-3. Results of the calibration and validation of the model using standard statistical techniques. Emboldened and highlighted rows indicate the best performing parameter sets which were used to estimate the parameters for the final model. The calibrated model used Manning's n of 0.03 ($m^{1/3} s^{-1}$) on the floodplain and 0.04 ($m^{1/3} s^{-1}$) in the channel, and a DEM resolution of 10m.

Parameter Tested			RMSE				NSE (vs Gauge)				C%
	Channel	**Floodplain**	**Hexham**	**Corbridge**	**Riding Mill**	**Bywell**	**Hexham**	**Corbridge**	**Riding Mill**	**Bywell**	
Mannings 'n'	0.02	0.03	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.04	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.05	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.06	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.07	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.03	0.03	0.235	0.407	0.370	0.247	0.953	0.944	0.948	0.983	90%
	0.03	0.04	0.354	0.590	0.501	0.385	0.895	0.884	0.904	0.958	89%
	0.03	0.05	0.354	0.590	0.501	0.385	0.895	0.884	0.904	0.958	89%
	0.03	0.06	0.332	0.538	0.456	0.338	0.907	0.903	0.920	0.968	89%
	0.03	0.07	0.319	0.508	0.430	0.312	0.915	0.914	0.929	0.972	89%
	0.04	**0.03**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	0.04	0.233	0.365	0.422	0.332	0.954	0.955	0.932	0.969	90%
	0.04	**0.05**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	**0.06**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	**0.07**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.05	0.03	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
	0.05	0.04	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
	0.05	0.05	0.235	0.348	0.466	0.393	0.954	0.959	0.917	0.956	86%

Parameter Tested		RMSE				NSE (vs Gauge)				C%
Channel	Floodplain	Hexham	Corbridge	Riding Mill	Bywell	Hexham	Corbridge	Riding Mill	Bywell	
0.05	0.06	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
0.05	0.07	0.319	0.508	0.430	0.312	0.915	0.914	0.929	0.972	89%
0.06	0.03	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
0.06	0.04	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
0.06	0.05	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
0.06	0.06	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
0.06	0.07	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
DEM Resolution	5	0.093	0.436	1.271	0.761	0.993	0.936	0.381	0.836	88%
	7.5	0.220	0.435	0.341	0.710	0.959	0.937	0.956	0.857	88%
	10	**0.288**	**0.487**	**0.443**	**0.320**	**0.930**	**0.920**	**0.925**	**0.971**	**89%**
	20	**0.204**	**0.261**	**0.359**	**0.514**	**0.965**	**0.977**	**0.951**	**0.925**	**89%**

Calibrated Model	RMSE				NSE				C%
	Hexham	Corbridge	Riding Mill	Bywell	Hexham	Corbridge	Riding Mill	Bywell	
Mannings 'n': *FP 0.03 Ch 0.04* *DEM resolution: 10m*	0.259	0.443	0.335	0.194	0.944	0.934	0.957	0.989	90%

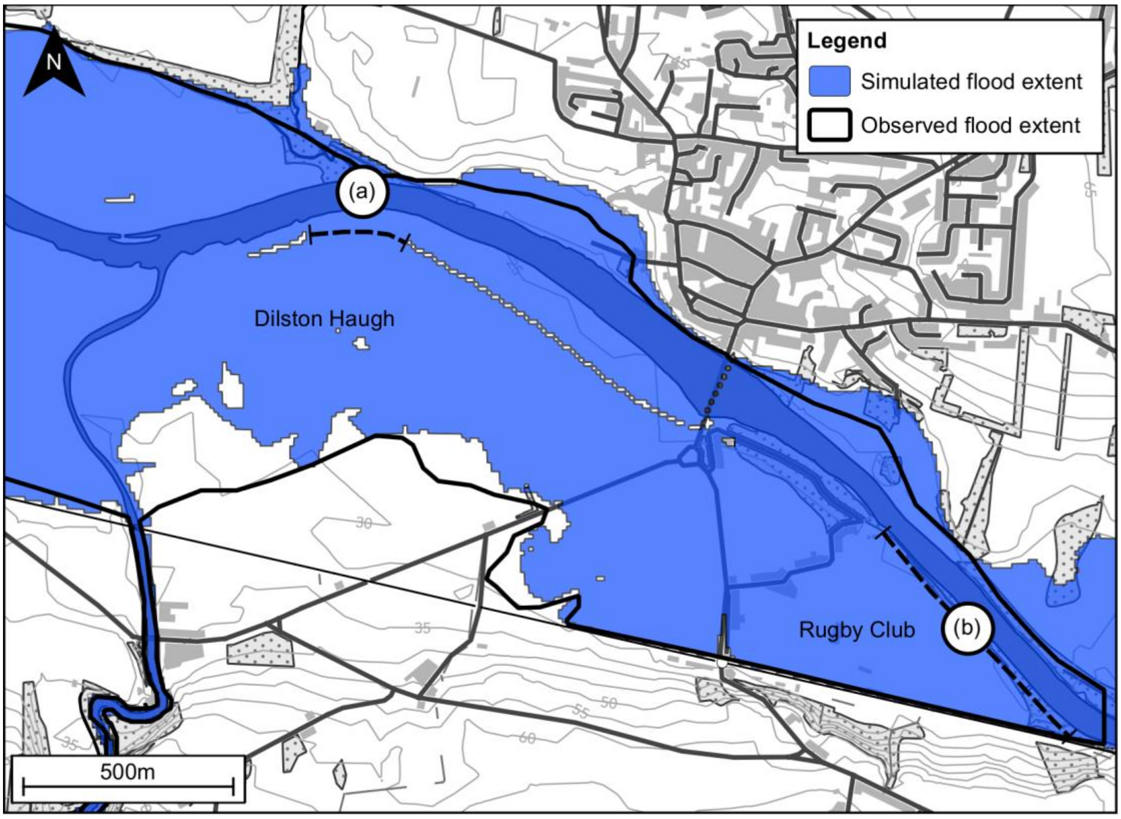


Figure 3-3. The predicted maximum flood extent produced by the calibrated model compared to the observed maximum extent derived from analysis of the UAV imagery. The results show that there was some variability in the under- and over-prediction of flooding on both banks. In particular, locations (a) and (b) showed areas of overtopping of the defences which were not observed, indicating that the bare earth DEM used for the model may contain inaccuracies which affected the flow of water across the floodplain.

3.4.2 Application of the experimental validation approach

3.4.2.1 Reconstruction of the 2015 event dynamics

Figure 3-4 shows the reconstruction of the dynamics of the December 2015 flood, undertaken using the VGI database. These can be divided into two types of dynamics: pathways of defence overtopping; and pathways of flow across the floodplain. The results indicated three pathways of defence overtopping (FP1, FP3, and FP4). FP1 and FP3 represented generalised overtopping of the defences (the extent of which is indicated on Figure 3-4), whereas FP4 was identified as a specific location of overtopping at the junction between two defence types, which resulted in a distinct flow of water onto the Cricket Club from the north.

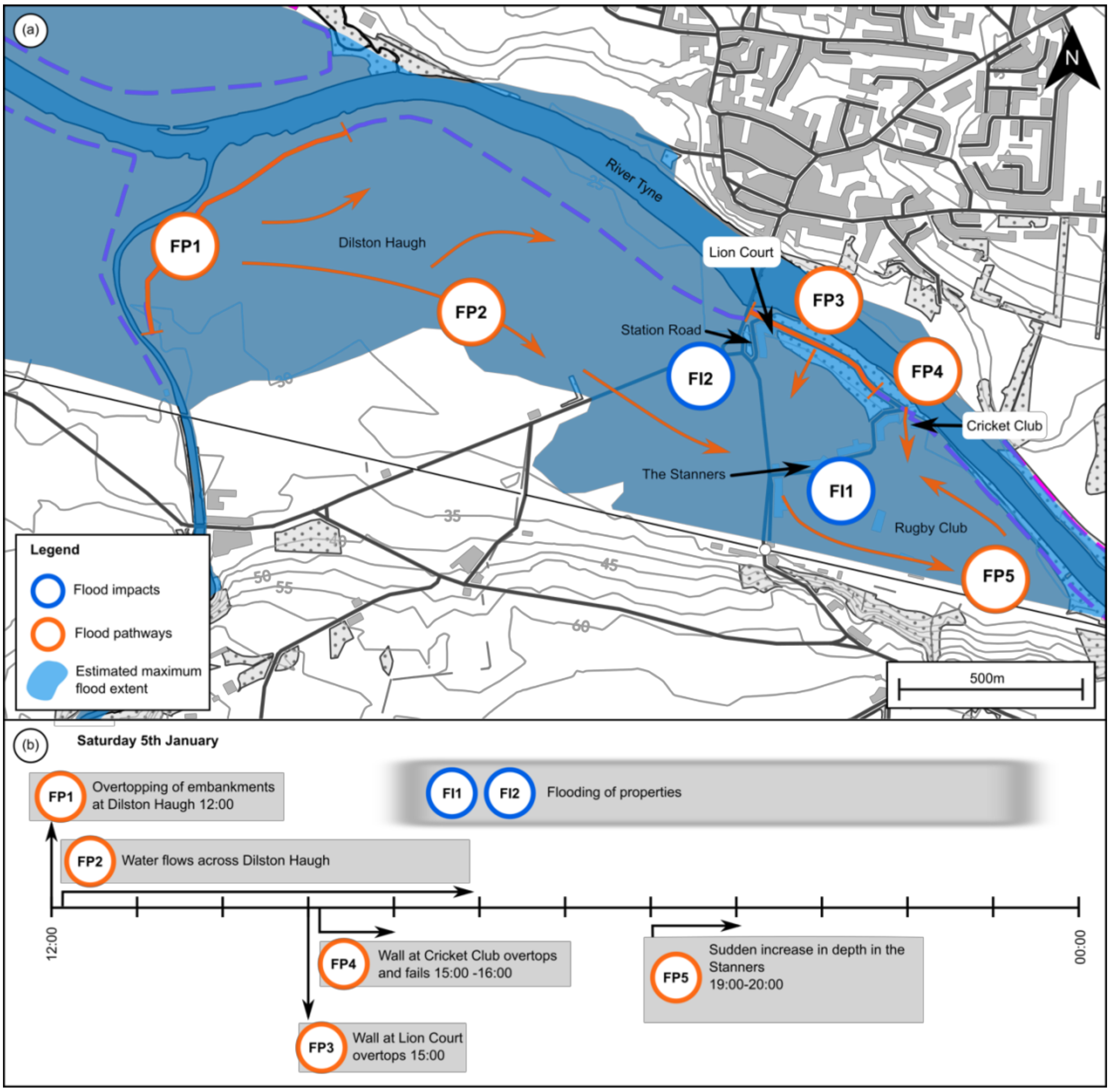


Figure 3-4. Reconstruction of the (a) spatial distribution of flood pathways and impacts, and (b) timings of the December 2015 flood using the VGI database. Pathways are referenced in order of occurrence. The reconstruction indicated three principle areas of overtopping, with two main pathways across the floodplain and two main areas of impact. The flood timings indicated that water began to overtop the Dilston Haugh defences at approximately 12:00 GMT on the 5th, with the overtopping of the Lion Court and Cricket Club defences occurring later. The sudden increase in flooding between 19:00 GMT and 20:00 GMT represented the backing up of flood waters from the Rugby Club as part of FP5.

Two pathways of flow across the floodplain were also reconstructed. FP2 represented a general flow from the upstream areas of overtopping following the topography of the floodplain. FP5 represented backing up of water that was unable to return back to the river as a result of the flood defence and the high water levels in the river. This was manifested in the data as a reported sudden increase in depth at properties between 19:00 and 20:00 GMT on 5th December. Two main areas of impact were also represented at The Stanners (Figure 3-4, FI1) and Station Road (Figure 3-4, FI2). Although the distribution of properties affected by the flooding event was greater than that shown, no data was available to validate the impacts in these other areas.

3.4.3 Results of the experimental validation

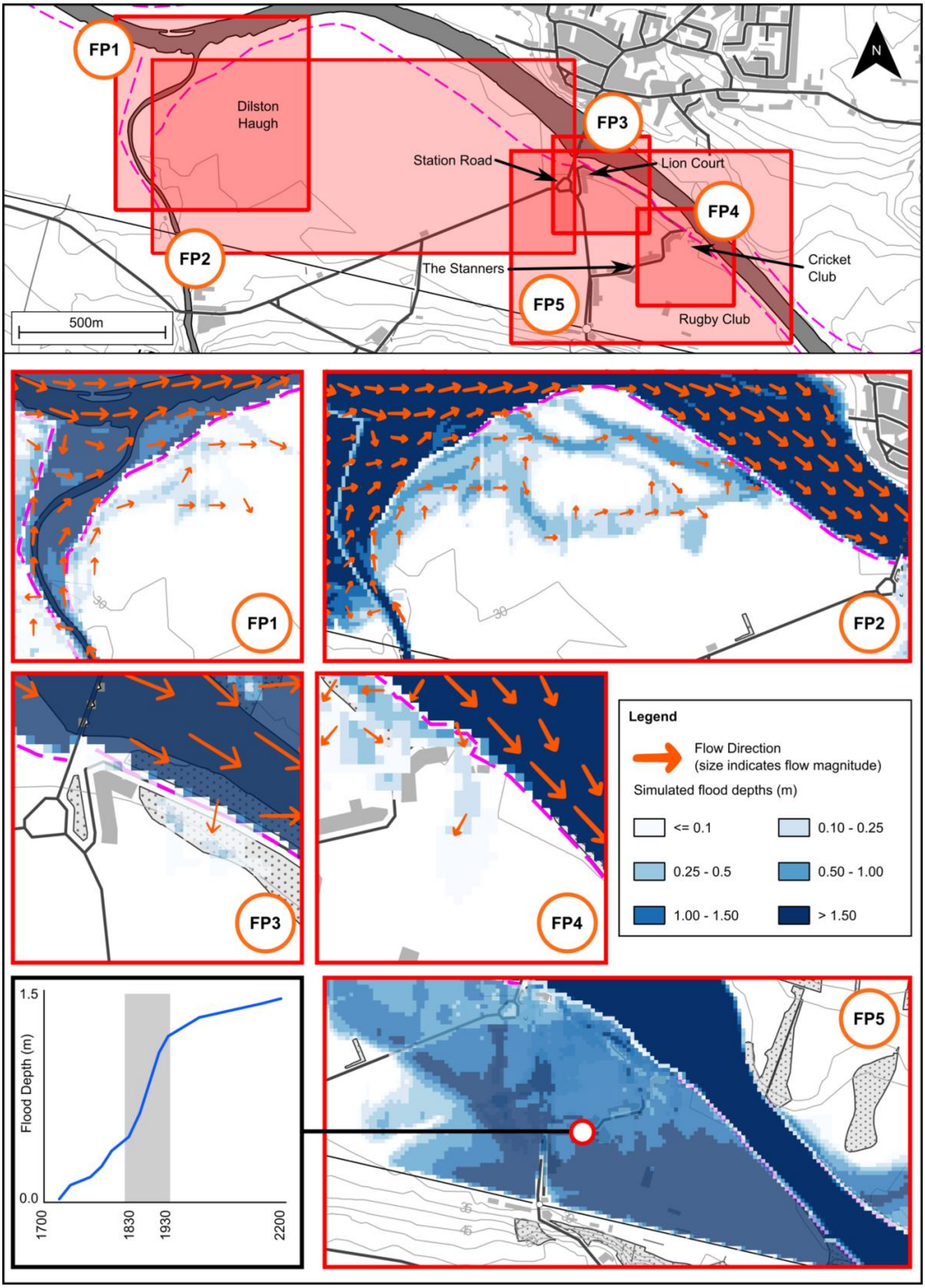
The calibrated model was validated against the key pathways, timings and impacts of the December 2015 flood identified in section 3.4.2.

3.4.3.1 Validation of flood pathways

Pathways were identified from the model simulation using 15 minute resolution time-series outputs of depth and velocity. Figure 3-5 shows the results of the validation. The results indicate that the model was successful in simulating all of the major pathways identified in the observed data. In the case of FP1 and FP2 the model showed general overtopping of the defences along Dilston Haugh and flow following low-lying areas of the floodplain topography, which are potentially relict river channels. This is further north on the floodplain than was interpreted from the VGI, and is considered to reflect error within the VGI rather than in the model. This is because these flow pathways were not directly observed by the research participants; instead they were inferred from the direction of flood waters which entered their homes. For FP3 and FP4 the model showed successful differentiation between the two pathways. FP3 was simulated as overtopping of the wall at Lion Court, and there is also a distinct overtopping location at FP4. This results in flow across the Cricket Club from the north, reported by research participants, which is separate to the other flooding at and around Lion Court.

The processes behind the time-line of FP5 were the most contested within the VGI, with participants reporting a sudden increase in depth at The Stanners and Station Road (Figure 3-5), but with considerable disagreement over the pathway this water had taken. Review of the flow vectors produced by the model for this area was not conclusive in identifying a simple backflow of water. However, calculation of the change in simulated inundation depth at The Stanners does show a significant increase in depth in the area which corresponds to the observed pattern and timing of flooding. This suggests that the model is accurately simulating the observed flooding situation. However, whether or not the processes underlying this simulation are accurate, cannot be validated with the available data.

Figure 3-5. Simulation results used for the validation of flood pathways. Validation was undertaken dynamically using GIS but for the purposes of static display results are extracted from the model for the time which corresponds with the flood pathway being demonstrated. FP5 shows flood depth change through time for the location on The Stanners indicated in the inset map and the graph highlights the rapid increase in depth shown by the simulation between 18.30 GMT and 19.30 GMT, corresponding with the conditions reported by research participants.


FP1
FP2
FP3
FP4
FP5
Dilston Haugh
Station Road
Lion Court
The Stanners
Cricket Club
Rugby Club
500m
N
Legend
Flow Direction
(size indicates flow magnitude)
Simulated flood depths (m)
<= 0.1
0.10 - 0.25
0.25 - 0.5
0.50 - 1.00
1.00 - 1.50
> 1.50
Flood Depth (m)
1.5
0.0
1700
1830
1930
2200

3.4.3.2 Validation of flood timeline

The success of the model at simulating the timings of the December 2015 flood was assessed based on the 15 minute resolution time-series animations produced by the model. Table 3-4 shows the simulated timeline against the observed timings and demonstrates that the model was successful at predicting the timings of pathways FP1-4 as it simulated the pathways in the observed order, and either at the correct time, or within the time-periods identified by participants. In simulating FP5, the model showed a significant increase in depth in these areas from 18.30 GMT onwards (Figure 3-5) where it showed a 30 minute offset from the observed time. However, it is also possible this offset reflected variation in the timing of the effect observed by participants rather than any error in the model itself.

Table 3-4. Results of the validation of Flood Timings showing that the model was, in the majority of cases, able to accurately simulate both the relative order of events and also their specific times reported by participants.

Pathway	Observed Time (GMT)	Simulated Time (GMT)
FP1	12:00	12:00
FP2	12:00 onwards	12:00 onwards
FP3	15:00 – 16:00	15:30
FP4	16:00 – 17:00	16:30
FP5	19:00 onwards	18.30 onwards

3.4.3.3 Validation of flood impacts

Section 3.3 has already outlined the partial validation of the flood extents of the 5th December 2015 flood event, which demonstrated that the model achieved 90% global accuracy in simulating maximum flood extent and water levels. However, the simulation of local water levels (and hence flood depth) can also be assessed using quantitative data on flood levels derived from imagery obtained across the area of interest. Eighteen images were collected as part of the research that could be used for the validation. Of these, 12 were capable of being used for validation of flood impacts, with 4 located along the Dilston Haugh flood defence, two each at the Stanners and Station Road, and three at the Cricket Club (Figure 3-5), providing coverage of the majority of the study area. Eight of these images provided information on the maximum flooded depth and could be used to quantify the variation in observed and simulated depths. Four images did not provide any direct information on maximum depths, but provided a minimum constraint to simulated maximum depths as they showed inundation depths on Sunday 6th December, on the waning limb of the flood hydrograph.

Table 3-5 shows that there was variable success in the simulation of local flood depths. Along the flood embankment at Dilston Haugh (Table 3-5, photographs 1-5), the model consistently underestimated flood depths overtopping the flood embankment by an average of 0.25m and up to a maximum of 0.50m. At The Stanners and the Cricket Club (Table 3-5, photographs 8, 9 & 12) the model was more successful, with the difference between interpreted and simulated depths of only 0.02m and 0.16m respectively. For those images which provided only a minimum constraint to the simulated depths, the modelled depth exceeded the minimum constraint in all cases. These results suggest that there were disparities in the way that the model simulated the flow of water into and/or out of the study area. The underestimation of depths along the Dilston Haugh defences suggested that this pathway was not correctly simulated, with too little flood water overtopping the defences at this location. That local flood depths at The Stanners and the Cricket Club were more accurate suggesting that overtopping at this location might be too great. These results were substantiated by the maximum extent results (Figure 3-3), which showed overtopping of the embankments at the Rugby Club, something not reported in the VGI database. Taken together, these results demonstrated that, at a local scale, simulation of inundation depths and extents was quite variable. This was despite the model showing high levels of accuracy at a global scale. These results likely reflect inaccuracies in the bare earth DEM which influenced simulated flow at a local scale. These inaccuracies could potentially have been introduced either during the pre-processing filtering process or during the resampling of the data from 2m to 10m resolution.

Table 3-5. Comparison of spot water levels obtained from photographs with simulated maximum water levels. Photographs representing maximum water levels allow direct comparison with simulated levels. Minimum constraints represent the minimum level of flooding that should be achieved by the simulation.

No.	Location - Description	Image category	Interpret-ed Depth (m)	Simulated Depth (m)	Difference (m)
1	Dilston Haugh Flood Defence - extent of overtopping and depths above flood wall	Max Level	0.4	0.325	-0.075
2		Max Level	0.4	0.279	-0.121
3		Max Level	0.5	0.210	-0.29
4		Max Level	0.3	0.030	-0.27
5		Max Level	0.5	0.001	-0.499
6	Station Road - flood waters remaining at Station Road roundabout on Sunday morning	Min constraint	0.4	0.826	0.426
7		Minimum constraint	0.4	0.995	0.595
8	The Stanners - maximum water level marks on property walls at property on The Stanners	Maximum Level	1.0	1.019	0.019
9		Maximum Level	1.0	1.019	0.019
10	Cricket Club - water ponding within Cricket Club on Sunday	Min constraint	1.0	1.594	0.594
11	Cricket Club - water mark on wall shows Sunday level	Min constraint	1.0	1.582	0.582
12	Cricket Club - water mark shows maximum depth at club house	Max Level	1.2	1.362	0.162

3.5 Discussion

This paper has introduced a new approach to flood model validation. The approach uses a VGI database collected during and immediately after a severe flood event to reconstruct and validate event dynamics. This approach builds on traditional, statistical approaches which are typically spatially or temporally limited and do not give a full picture of how an inundation model is performing at a local scale. The approach has been tested using a VGI database collected following a severe flood which occurred at Corbridge, UK in December 2015.

3.5.1 Evaluating the success of the experimental validation method

The results of the research demonstrate that the experimental approach offers a more comprehensive validation of event dynamics than offered by traditional statistical approaches. At a global scale, established quantitative validation methods were used to assess the goodness-of-fit between simulated and observed water levels at river gauges, and between observed and simulated maximum flooded extents. The simulation shows RMSE values of <0.5 and NSE values of >0.9 at all available gauges, and a 90% accuracy in simulating the observed maximum extents. This is equal to or better than other similar modelling studies using LiSFLOOD-FP (Renschler and Wang, 2017; Wing et al., 2017), and suggests that the model is successfully simulating the inundation seen during the December 2015 flood event.

However, these established metrics only provide an incomplete, spatially and temporally limited, validation of the model performance (Hunter et al., 2007). The results of the experimental method outlined indicate that the more comprehensive validation is able to identify areas of model under-performance not identified by established global statistical approaches. In particular, the experimental validation shows that, although the model accurately simulates the timeline and locations of flood pathways, it incorrectly simulates the processes of overtopping and consequently local inundation depths. These results likely reflect localised inaccuracies in the underlying 10m resolution DEM used for the model or the need for greater spatial variability in the parameterisation of roughness, both which could influence the flow of water across the floodplain which is not identified at a global scale. This would have potentially serious consequences if the model was to be used for local emergency response planning, or informing, for example, population evacuation strategies (Simonovic and Ahmad, 2005).

3.5.2 VGI data as an alternative to 'established' data sources

Figure 3-6 categorises the data used in the study according to its qualitative-quantitative nature and its degree of certainty, in comparison to more established data sources. Figure 3-6 shows how the VGI data is set apart from traditional data in its range of sources and how it comprises a blend of quantitative, semi-quantitative, and qualitative data. The study demonstrates that this range of data sources makes it possible to understand and reconstruct flood event dynamics using the VGI data as a standalone dataset. As shown through the validation of the flood timeline, and local scale pathways and impacts presented here, VGI data offers opportunities for validating aspects of the flood inundation models at spatial and temporal scales which would be almost impossible using traditional means. This makes VGI a valuable alternative to traditional data sources, not just for immediate post-disaster response and recovery (Haworth and Bruce, 2015), but also as a longer term source of data to inform scientific analysis (Granell and Ostermann, 2016). This range of data sources has also been shown to be important to achieving a valid VGI dataset, particularly where a mixture of qualitative-quantitative data prevents the application of statistical metrics. Previous studies using more single-format databases have highlighted data validity as a limitation of VGI data (e.g. Klonner *et al.*, 2016). However, we have demonstrated the usefulness of adopting a much more flexible and interpretative model of data assessment based on triangulation with different data sources (Mays and Pope, 2000; Sousa, 2014; Wiggins and He, 2016).

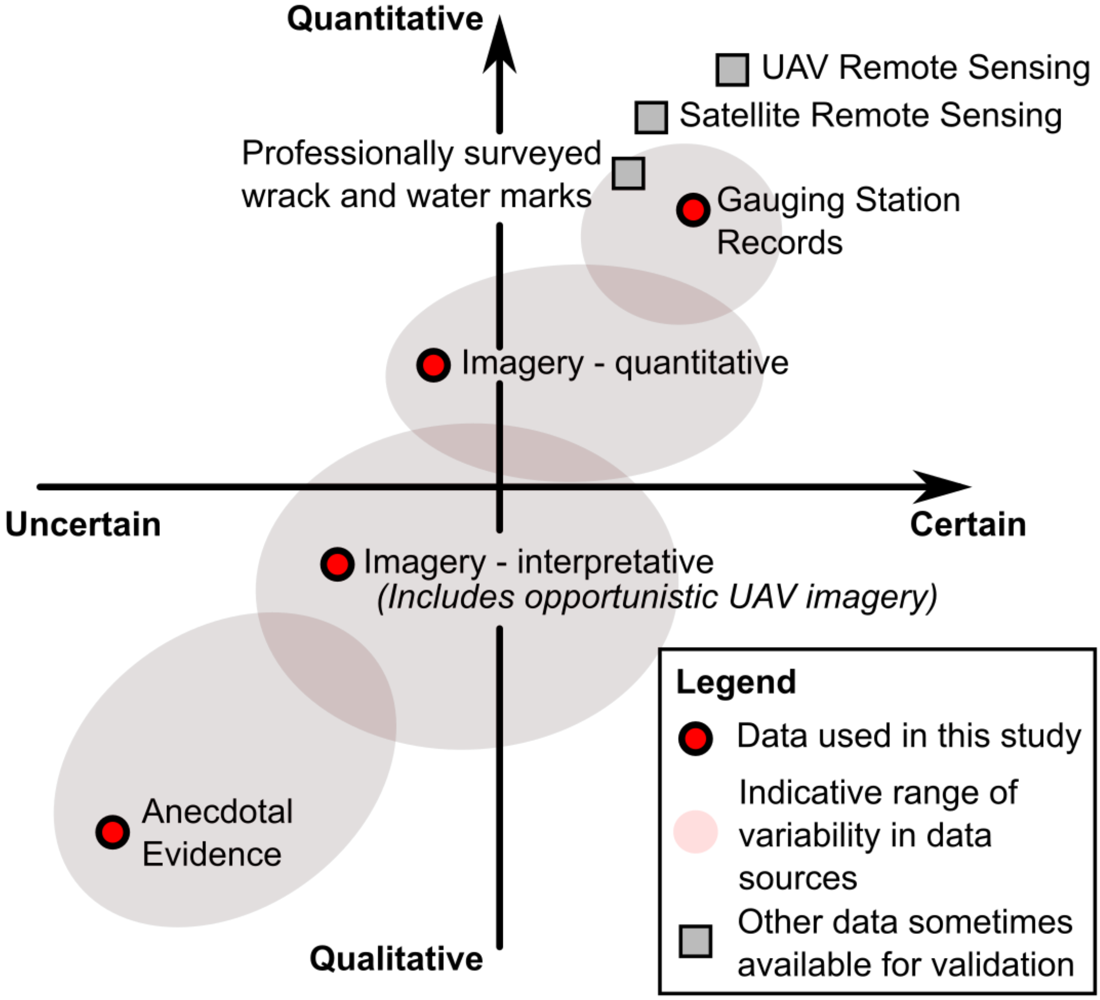


Figure 3-6. Categorisation of the VGI datasets collected and used in this study in comparison to established datasets used for model validation. Quantitative imagery are those imagery from which direct quantitative measurements can be made (e.g. wrack marks), whilst interpretative imagery provide non-quantitative indicators (e.g. flow pathways), including opportunistically collected UAV survey data.

3.5.3 A new framework for validating flood inundation models

This study has demonstrated a new approach to the validation of flood inundation models, with the aim being simulation of underlying event dynamics through better incorporation of VGI. The study has also demonstrated the usefulness of community-generated, VGI data as a primary input to the future validation of flood models. Building on these findings, we suggest a new framework for the validation of flood models (Figure 3-7).

The proposed framework builds on current statistical approaches to validation by recognising the ability of current numerical models to simulate complex event dynamics, and the wider diversity of data which this study has shown to be applicable to model validation. The framework represents a three-stage process:

1. Data processing – The framework encourages a flexible and researcher-driven approach to assessing data validity which should reflect the data collected in its methods and outcome. As the fields of citizen science and VGI continue to evolve and mature, new practices of data collection and quality assessment will no doubt emerge (Granell and Ostermann, 2016; Hung et al., 2016). Greater standardisation through structures such as Citizen Observatories represent one way in which data collection might be expanded and improved (Lanfranchi et al., 2014; Wehn et al., 2015). Future improvements in personal technology will also likely make UAV data (Perks et al., 2016; Smith, 2015) and geo-located citizen data from personal electronic devices (Newman et al., 2012; Tang et al., 2017) more widely available. Taking these potential future developments into account, the framework aims to encourage the use of a wide range of data in many formats to allow cross referencing and triangulation between data sources.

2. Event Dynamics – The framework proposes *pathways*, *timeline*, and *impacts* as broad categories through which principle event dynamics can be defined. This includes the traditionally assessed metrics of in-channel gauged levels and maximum inundation extents, but recognises that for many uses the parameterisation of numerical models in terms of these metrics alone is overly simplistic. By assessing a wider range of *processes* within the framework we can develop a more holistic validation and ensure that the dynamic simulation capabilities of modern numeric models are exploited to their full potential.

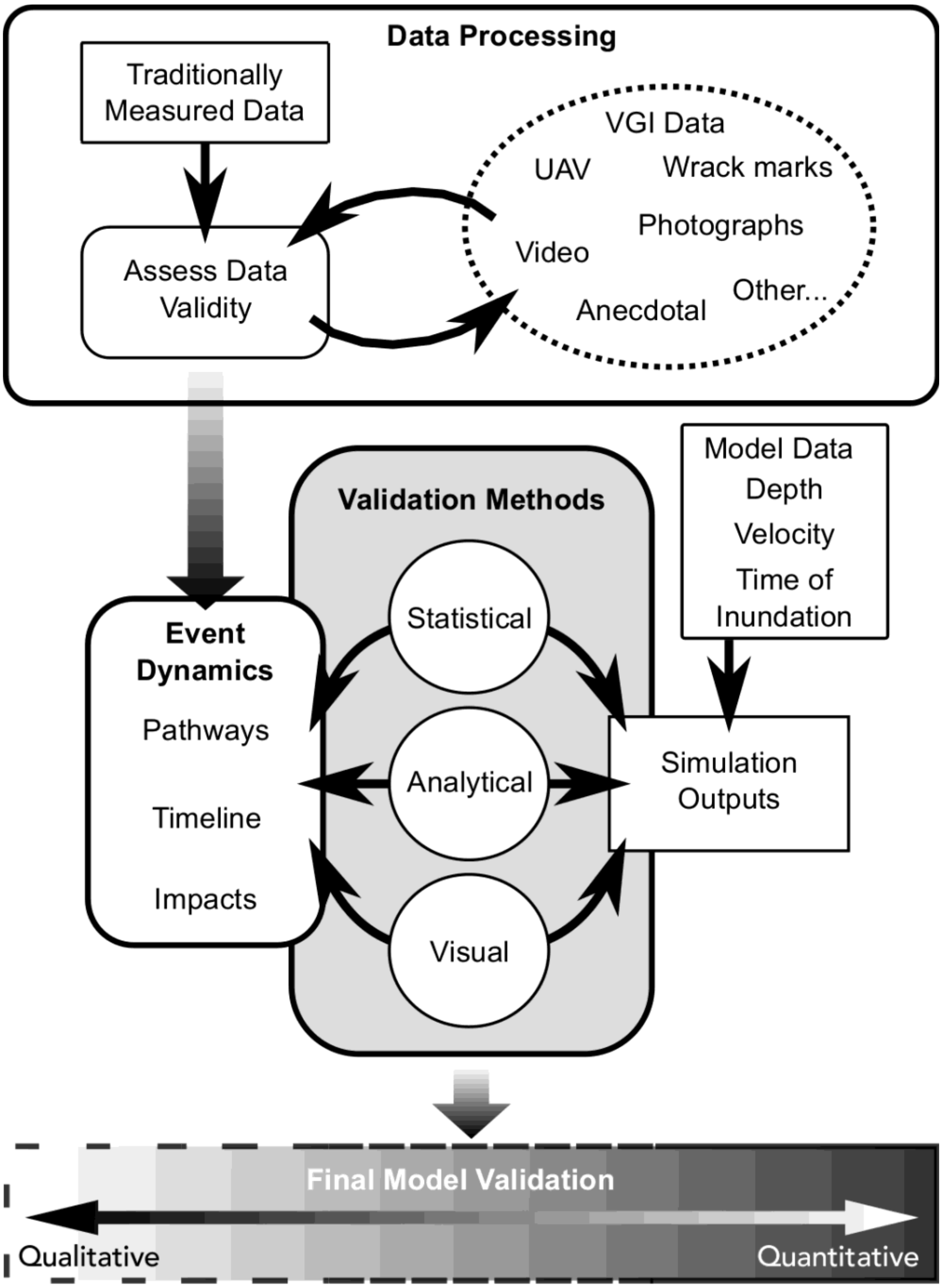


Figure 3-7. A new framework for the validation of flood inundation models. The framework reflects the flexibility demonstrated in the study in using non-standard data sources to examine the underlying dynamics of flood events simulated by modern inundation models. The results of the validation reflects the diverse nature of the data and the validation methods which can be applied, and in so doing accepts a reduced quantified rigour in return for achieving a more comprehensive understanding of complex event dynamics.

3. Validation Methods – The framework adopts the same flexible approach to the validation of simulated dynamics as to data assessment. This recognises that different input data, simulations, and dynamics require different approaches to validation. Three broad types are proposed: *statistical*, incorporating established performance measures (Wing et al., 2017); *analytical*, reflecting semi-quantitative approaches such as the analysis of UAV footage and quantitative imagery demonstrated by this study; and *visual*, encompassing all techniques which rely on 'on the face of it' validation (Rykiel, 1996). The latter would include the assessment of pathways against the dynamic simulation outputs demonstrated in this study. The balance of validation techniques should reflect both the availability of simulation outputs and the availability of suitable data against which to validate them.

The final validation produced by the framework is a flexible one, influenced by the dynamics of the event, the data available, and methods adopted. The final result will likely lack the quantitative rigour of established statistical methods. Based on the results of this study we propose that some degree of inaccuracy and uncertainty can be accepted in return for the benefit of achieving a more comprehensive understanding of complex flood event dynamics (Granell and Ostermann, 2016). By adopting a more flexible approach to using VGI data in this way we can improve model validation, and, furthermore, open up the currently expert-led practices of flood risk assessment to greater public participation (Usón et al., 2016).

3.6 Conclusions

Numerical models are the foundation of flood risk assessment and management, used for understanding and mapping areas at-risk from floods and planning management interventions. Recent improvements in computing power and model code, and increases in the availability of spatially distributed data on floodplain environments have increased the popularity of 2D models for providing detailed simulations of complex flood dynamics. However, improvements in model simulations have not been accompanied by corresponding improvements in model validation. Due to a lack of data from, during, and immediately after flooding events, validation of flood inundation models still grounded in the statistical assessment of spatially and temporally limited datasets, such as remotely-sensed flood extents or in-channel river gauging. The research presented in this study has demonstrated a new approach to the validation of flood inundation models, using VGI data to provide information on event dynamics not captured by traditionally measured datasets. In so doing, we have demonstrated that:

1. By collecting a wide range of VGI data from multiple sources it is possible to reconstruct in detail the dynamics of a severe flood. Although statistical validation is less rigorous, the quality of this reconstruction can be assessed through data triangulation and other qualitative approaches.
2. The reconstruction of flood pathways, timeline, and impacts of flooding can be used to validate the dynamic outputs of a 2D flood inundation model, and allow both spatial and temporal examination of model performance in simulating flooding processes.
3. The experimental model validation approach tested here enhances existing global statistical approaches to validation by examining the simulation of underlying flood processes using the case study of a large flood on the River Tyne, UK. The results of the test case indicate that a model assessed using traditional methods as having a global accuracy of over 90% in simulating gauged river levels and maximum flood extent does not accurately represent the actual pathways and impacts of the event. This is potentially highly

significant when models are used in a dynamic way to plan and assess floodplain management interventions.

Drawing on these conclusions we propose a new, flexible framework for the validation of flood inundation models. In contrast to current approaches, the framework encourages the use of a diverse range of non-traditional data, now and into the future. Similarly, the framework encourages a mixture of approaches to validation to be adopted, leading to more flexibility depending on data availability and aspects of the simulation being considered. Although the final validation may lack the quantitative rigour of established global approaches, it provides a more comprehensive and bespoke examination of the model’s performance, particularly for situations where dynamic model outputs are being used to inform potential floodplain interventions.

The results shown by this study also demonstrate the value of alternative data sources such as VGI, or data collected from citizen science programmes, to enhance and extend established data sources. We have demonstrated that many of the common criticisms of alternative data being ‘messy’ and unscientific can be understood or overcome by relatively simple procedures for quality control such as triangulation. However, data is, as demonstrated by other studies, not always as diverse or spatially distributed as that collected in this study, a fact that must be considered when translating this approach to other areas. For triangulation to be effective a mixture of overlapping data from different informants and from different sources (e.g. anecdotal, remote sensing, imagery) is essential. Additionally, all of these data need to be located, both spatially and temporally, within the study area or event of interest. This necessitates further research on the development of data collection approaches which combine the locally situated engagement adopted in this study with structured data collection approaches of citizen science or citizen observatories, and the spatial coverage of technology-based VGI approaches.

With predicted increases in the risk of flooding as a result of future climate change, numerical models are likely to continue to represent a significant asset in flood risk assessment practices. The VGI framework proposed here represents a more comprehensive process of model validation based on the more effective use of alternative data sources. This has the benefit of both allowing more comprehensive exploitation of modern numerical modelling to better simulate complex river-floodplain interactions and also encouraging the exploration and use of diverse datasets which may open up new perspectives on the use of numerical models for the creation flood risk knowledge. To effectively integrate the proposed validation framework into future modelling work, further research is urgently required in order to explore how technological VGI solutions could be developed to allow the routine collection of flood data through local engagement platforms such as citizen observatories.

[Page Left Intentionally Blank]

Chapter 4 Rethinking flood risk communication

Overview: This paper presents the results of a participatory research experiment conducted with participants from a study site in the northeast of England. Through the mechanism of an environmental competency group, the research analyses current flood risk communication approaches intended to build local community resilience. Using their experiences from a recent extreme flood, the group participants co-created a suite of prototype designs for new flood risk communications specifically designed to meet their information needs and develop their resilience.

Motivation: The purpose of this paper was the further develop the themes identified in Chapters 2 and 3 by demonstrating how deep participation could be embedded into the development of new practices of knowledge creation. By combining expert knowledge and skills with local knowledge and experiences, the research shows how better and more applicable shared knowledges can be created to help develop community resilience to extreme flood events.

Citation Information: This paper was published in Natural Hazards as Rollason E, Bracken LJ, Hardy RJ, Large ARG (2018) Rethinking flood risk communication. Nat Hazards 1–22. doi: 10.1007/s11069-018-3273-4.

Author Contributions: In this paper, I designed the research methodology, undertook the empirical data collection, wrote the text, created the figures and led the paper development. My co-authors provided editorial input and guidance on the development of the paper.

4.1 Introduction

Flooding is a major hazard throughout Europe (de Moel et al., 2009) with over 2.4 million properties potentially at-risk (Environment Agency, 2009). Over the last decade Flood Risk Management (FRM) has evolved to develop and enhance community resilience to flooding, rather than controlling flood waters using engineering solutions (Van Alphen et al., 2009). Communication of flood risk information is a key element of FRM which aims to "*strengthen people's risk awareness and to motivate the population at-risk to take preventive actions and to be prepared*" (Hagemeier-Klose and Wagner, 2009, p. 564). Communication of flood risk is a valuable way to link expertise and management undertaken by practitioners with the development of local-level resilience in an at-risk community (Butler and Pidgeon, 2011; de Moel et al., 2009).

Flood risk communication encompasses two phases: firstly, identifying areas at-risk of flooding; and secondly, letting those at-risk know when flooding is likely to occur. Both phases are crucial to helping those at-risk prepare for, anticipate and act to lessen the consequences of flood events. This is a vital element of developing community resilience; flood impacts can be significant, and extend beyond those whose homes are flooded, and for prolonged periods following a flooding event. For instance, research has demonstrated that flooding can result in increased morbidity (Milojevic et al., 2017), increase the occurrence of infectious diseases (Waite et al., 2017), and cause significant, long-term mental health impacts (Lamond et al., 2015) including depression, anxiety and post-traumatic stress disorder (Munro et al., 2017). As well as helping people take action to reduce the impact of floods on their homes and to evacuate areas of high flood hazard, flood risk communications have also been shown to have a significant impact on reducing longer-term impacts. For example, Munro *et al.* (2017) demonstrate that receiving timely warning prior to a flood was the only factor likely to limit the impact of flooding on mental health. Communicating flood risk prior to and during events is thus crucial to limiting flood impacts and ensuring well-being in at-risk communities.

This paper explores current flood risk communications, their effectiveness in promoting resilient behaviours and introduces new ways in which information could be presented to increase action to limit flood impacts. This assessment focuses on the approaches adopted in Europe following the introduction of the European Union Floods Directive (EUFD) (European Parliament and the Council, 2007), which has resulted in a unification of communication approaches between countries within the

EU. We employ a case study in the UK, where we work with a community that have previous experiences of flooding to (i) examine existing approaches to flood communications, (ii) explore how we can work with at-risk participants to develop new ways of thinking about the content of flood risk communication, and (iii) use participatory approaches to co-produce a series of prototypes for more effective flood risk communications.

Research in psychology has explored the way in which risk messages are translated into behaviour by those receiving them (for examples see Slovic *et al.* 1974; Fischhoff *et al.* 1993; Burns and Slovic 2012; Bubeck *et al.* 2012). However, in the translation of this research into risk communication practice, those at-risk are often framed as needy, and reliant on experts to dictate what-risk information is important and why (Willis et al., 2011). This means at-risk communication users are often excluded from the processes of creating risk communications. By adopting participatory practices, and working together with those at-risk, the research presented in this paper looks to circumvent this framing by allowing research participants to determine what information is important to them for understanding their risk and increasing their resilience.

4.2 Current approaches to communicating environmental risks

The communication of environmental hazards and risks has a long and well developed history (Kasperson and Stallen, 2012), and strategies for risk communication can be seen applied to a wide range of environmental and technical risk and hazards. These include occasional, extreme events such as earthquakes, floods, or technological disasters (Lundgren and McMakin, 2018), and longer term, ‘creeping’ issues such as climatic change (Spence and Pidgeon, 2010).

Risk communication is often developed on a source-receiver model, where experts or agencies act as sources of centralised, expert information on the nature and impacts of hazards, communicating this information to the public (Mcquail and Windahl, 2015). Approaches to communicating this information vary significantly, however, research has highlighted the importance of vizualisation in communicating risk information (Zipkin et al., 2014), and such mapping approaches, which aim to communicate the spatial extent of potential zones of hazard or risk (EXCIMAP, 2007a), are a predominate communication method. A wide variety of mapping approaches also exist. Some focus purely on communicating hazard extents and characteristics, for example seismic hazard maps (Akkar et al., 2018), although in some cases the communication of risk information, i.e. incorporating hazard impacts and vulnerability, has been undertaken (Rahman et al., 2015), as well as visualisation of the potential probability of hazards occurring (Sørensen et al., 2012; Strathie et al., 2015). As well as the visualisation of hazard and risk information, research has also highlighted the importance of how, when, and by whom information is communicated (Steelman et al., 2015; Steelman and McCaffrey, 2013). This has particularly been driven by recognition of the importance of developing trust in communications and its role in translating risk communication into protective action (Paton, 2008; Steelman and McCaffrey, 2013; Terpstra, 2011).

4.2.1 Flood Risk Communication

Across Europe, the 2007 EUFD established common standards for the preparation of flood hazard and flood risk maps (EXCIMAP, 2007a). The UK provides a good example of these products, with the Environment Agency (EA) publishing a well-developed suite of different mapping types available online (de Moel et al., 2009). In addition to these mapped products sit an array of supporting communications (Table 4-1), as well as regular mass media communications programmes under the strapline “Floods Destroy, Be Prepared (https://floodsdestroy.campaign.gov.uk/). These include communication of real time river levels and flood alerts and warnings, intended to highlight the short-term potential for flooding.

Table 4-1. Flood risk communications approaches in England and Wales.

Communications Approach	Description and purpose of the communications
Flood Hazard and Risk Maps	These online maps indicate areas of potential flood hazard and differentiate high, medium, and low risk categories. Intended to raise awareness of the risk of flooding of those living in at-risk areas. Common to the majority of countries in the EU (de Moel et al., 2009; EXCIMAP, 2007b, 2007a).
Real-time water level information	Hydrographs of ‘real-time’ river levels monitored at river gauging stations provided online. During flooding conditions these records are updated at 15 minute intervals. These hydrographs also display the level over which flooding can be expected and the highest level ever recorded. Intended to allow local people to monitor local river levels and decide when to take action in response to potential flooding.
Flood Warnings (Flood Information Service, n.d.)	A flood warning system is also implemented across England (Fielding et al., 2007). Three alert levels are provided, the intention being that those at-risk should begin to monitor local river levels at the Flood Alert stage and begin to implement flood resilient actions at a Flood Warning Stage. Intended to instruct those at-risk when to take action in response to a potential flood.

The EA’s prime purpose for flood risk communications is to encourage participation in local FRM and develop community resilience (Environment Agency, 2011). EA research on resilience has previously focused on generating trusted, long-term relationships with at-risk communities (Twigger-Ross et al., 2014, 2011) (Table 4-1). As a result, communications have traditionally been supported by a network of local flood groups and wardens, tasked with working alongside the EA to prepare local communities for flooding (Gilissen et al., 2016). However, recent high profile floods have caused a shift of focus towards infrastructure and property-based resilience programmes (Chatterton et al., 2010; Environment Agency, 2011; McBain et al., 2010). As a result, community-based resilience has become somewhat of a secondary objective, and the potential for risk communications as an enabler of resilience has taken on a much greater level of importance (Environment Agency, 2010). However, existing research suggests that current communications are having limited impact on driving risk awareness or resilient behaviours. O'Sullivan *et al.* (2012) examined the impact of flood risk communications across Europe and identified low levels of information penetration and personal preparedness, often accompanied by a high level of distrust in communications and management organisations. In the UK, a 2016 EA poll indicated that only 45% of people living in at-risk areas appreciate their risk, and only 7% identify any risk to their own property (Environment, Food and Rural Affairs Select Committee, 2016). Similarly, independent polling by the '*Know Your Flood Risk*' campaign (Davies, 2015) reported that 31% of at-risk households surveyed had no flood plan and would not know what to do in the event of flooding.

4.3 Risk communication approaches and the adoption of resilient behaviours

Research has therefore identified that the existing UK model of flood risk communication is not functioning as intended, with communications failing to meet user needs or match their experiential knowledge (Environment Agency, 2010; Fisher, 2015; Meyer et al., 2012). It has also been argued that by centralising and professionalising the production of risk information, local communities lose their ability to properly understand their local risk situation (Bubeck et al., 2012; Lane, 2012). The outcome is that both the practice of communicating risk information and how information receivers interpret information may not actually be aligned with the stated purpose of flood risk communications in the UK. In this section we explore the fundamental research that underpins risk communication.

Callon (1999) and Demeritt and Norbert (2014) have both proposed models for how risk is communicated, considering the direction of communication, the roles of the communicator and the receiver, and the purpose of the communication (Table 4-2).

Flood risk communications have a joint purpose of both transmitting information and also altering behaviour (Hagemeier-Klose and Wagner, 2009) and can therefore be seen as a hybrid of the Risk Message Model (RMM) or the Public Education Model (PEM), and the Risk Information Model (RIM). Research driving RIM focused communications has explored a wide range of potential factors which influence the translation of risk information into behaviours: examples include previous experiences of a threat (Fielding et al., 2007; Hopkins and Warburton, 2015); cultural, geographical, and socio-economic factors (Bubeck et al., 2012; Burningham et al., 2008); reliance on public flood protection (Terpstra and Gutteling, 2008); trust/distrust in communications from a management authority (Terpstra, 2011; Wachinger et al., 2013); or a need to protect an individual's sense of personal security against high levels of future uncertainty (Harries, 2008; Willis et al., 2011).

An alternative approach to examining individual variables is proposed by Rogers (1975), who presents the Protection Motivation Theory (PMT) model (Figure 4-1). PMT explains and provides an overarching framework for the interplay between the disparate variables which may contribute to triggering behavioural responses from risk information. Rogers (1975) argues that individuals make their decision by appraising the severity and likelihood of their exposure (the threat appraisal) against the potential efficacy of potential protective behaviours (the coping appraisal), with their protection motivation representing the intervening stimulus which determines their actions.

Grothmann and Reusswigg (2006) and Bubeck *et al.* (2012) build upon Roger's work by expanding the sub-components of the threat and coping appraisals (Figure 4-1), as well as identifying the potential for non-protective responses such as denial or wishful thinking, in situations where threat and/or coping appraisals are negative. This concept is supported by research on 'learned helplessness' (Paton and Johnston, 2001), where individuals see disaster events as uncontrollable and therefore assume that their impacts are in turn uncontrollable (Paton and Johnston, 2006).

Table 4-2. A comparison of the defining characteristics of risk communications models proposed by Callon (1999) and Demerit and Norbert (2014).

Model	Direction	Role of Communicators	Role of Receivers	Purpose of Communication
Demerit and Norbert				
Risk Message	One	Educator	Passive	To inform[a]
Risk Instrument	One	Educator	Passive	Behavioural alteration
Risk Dialogue	Two	Active participant	Active participant[b]	To inform Behavioural alteration
Risk Governance	Integrated[c]	Active participant	Active participant	Encourage participation Create new knowledge /viewpoints
Callon				
Public Education	One	Educator	Passive	To inform[a]
Public Debate	Two	Active participant[d]	Active participant[e]	To inform[a]
Co-production of Knowledge	Integrated[b]	Active participant	Active participant	Create shared knowledge/ viewpoints[f]

[a] Assumes rational action from receivers.

[b] Who should participate, why, and how is seen as contested and dependent upon the purpose of the communication.

[c] Blurring of roles between knowledge producers and receivers.

[d] Privileged knowledge producers.

[e] Local knowledge intended to enrich scientific knowledge.

[f] Development of knowledge and viewpoints which are developed through the participatory process and are therefore shared by all participants.

PMT demonstrates the complex, contested, and highly personal nature of the linkage between communication and the adoption of protective behaviours. Comparison against the models of communication reveals the likely limitations of current communications approaches based on the RIM or PEM. These approaches, which assume a rational response from the receiver, are unlikely to address the complex nature of the threat and coping appraisals.

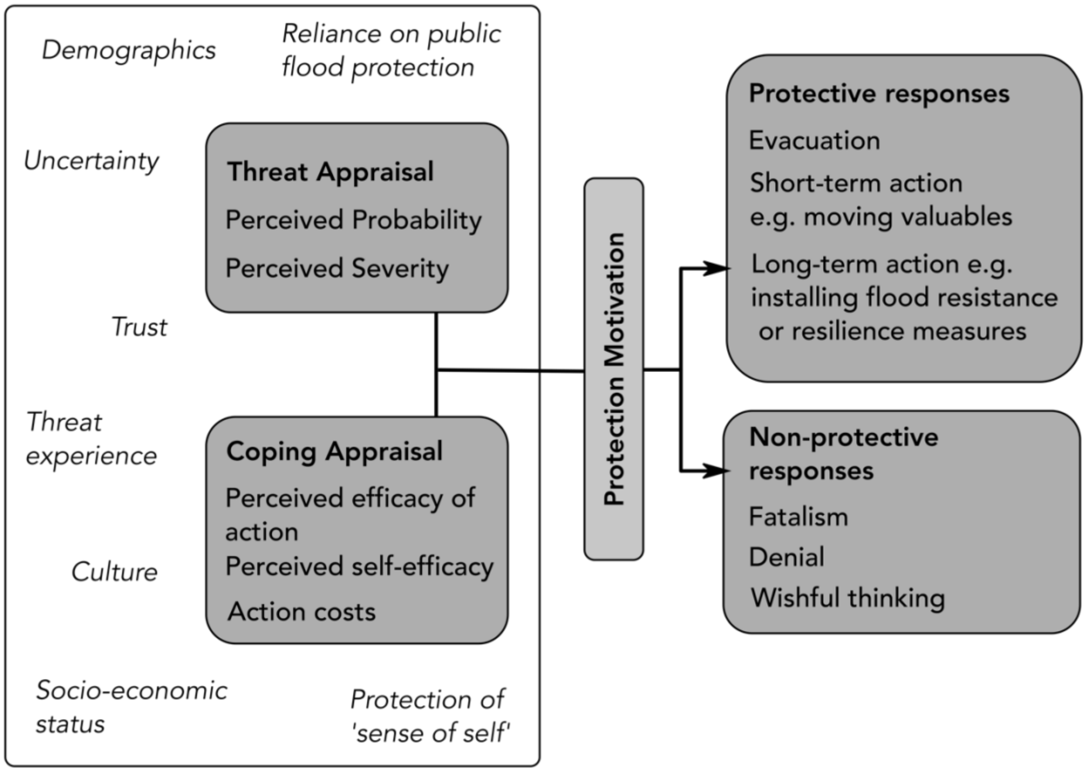


Figure 4-1 The Protection Motivation Theory Model. Factors influencing a decision to take protective or non-protective action in response to a threat. Shaded areas denote the PMT as proposed by Rogers (1975) and developed by Bubeck et al. (2012), whilst unshaded areas denote individual factors which have been shown to impact on threat and coping appraisals and therefore an individual's protection motivation.

4.4 Using participatory approaches to develop new ways to communicate flood risk

We suggest that participatory working (Kindon et al., 2007a) offers an opportunity to position people at the heart of flood risk communication and rethink how information can be communicated to those at-risk. Participatory working reimagines the traditional roles of expert and lay-people (Bucchi and Neresini, 2008; Landström et al., 2011; Lane et al., 2011b) and considers circulation of different forms of expertise (Whitman et al., 2015), with participants working together as equals to co-produce shared knowledge and outputs (Mees et al., 2016). Participatory working approaches have been applied to a variety of environmental problems, including the co-production of options for managing local flood risk (Lane et al., 2011b), the breaking down of borders between different organisations, professionals, and lay-people involved in catchment scale land management to manage floods (Bracken et al., 2016), and in developing end-user specific research outputs regarding agricultural pollution (Whitman et al., 2015). To date however, participatory practices have not been applied to flood risk communications, with recent research concluding only that participation was a useful approach for raising awareness or communicating flood risk complexity (Environment Agency, 2012), or as a way of providing limited feedback on current communications approaches (Fisher, 2015). These limited approaches to participation thus fail to exploit the potential of participatory working to open up the debate on what-risk information is important and why. Here therefore we look to expand the participatory approaches demonstrated by previous studies into exploring the efficacy of current flood communications and, working together with a flood group of flood affected locals, to co-produce alternative communications better suited to driving resilient behaviours.

4.4.1 The Corbridge Study Area

Corbridge (Figure 4-2) has a long history of flooding; approximately 70 properties in Station Road and The Stanners are situated on the floodplain and are vulnerable to flooding. River level records date back to the 1700s (Archer et al., 2007a), and the area has a long history of flooding, including flooding in 2005 resulting from the collapse of a flood defence embankment (Archer et al., 2007b). This earlier damage led to flood defence improvements being carried out by the EA prior to a major flood on 5th December 2015, an event with an estimated return period of between 100 and 200 years (Marsh et al., 2016), which exceeded the design standard for the defences leading to serious flooding. All 70 at-risk properties were reported to have been flooded (Environment Agency, 2016), some to depths of >1.5m.

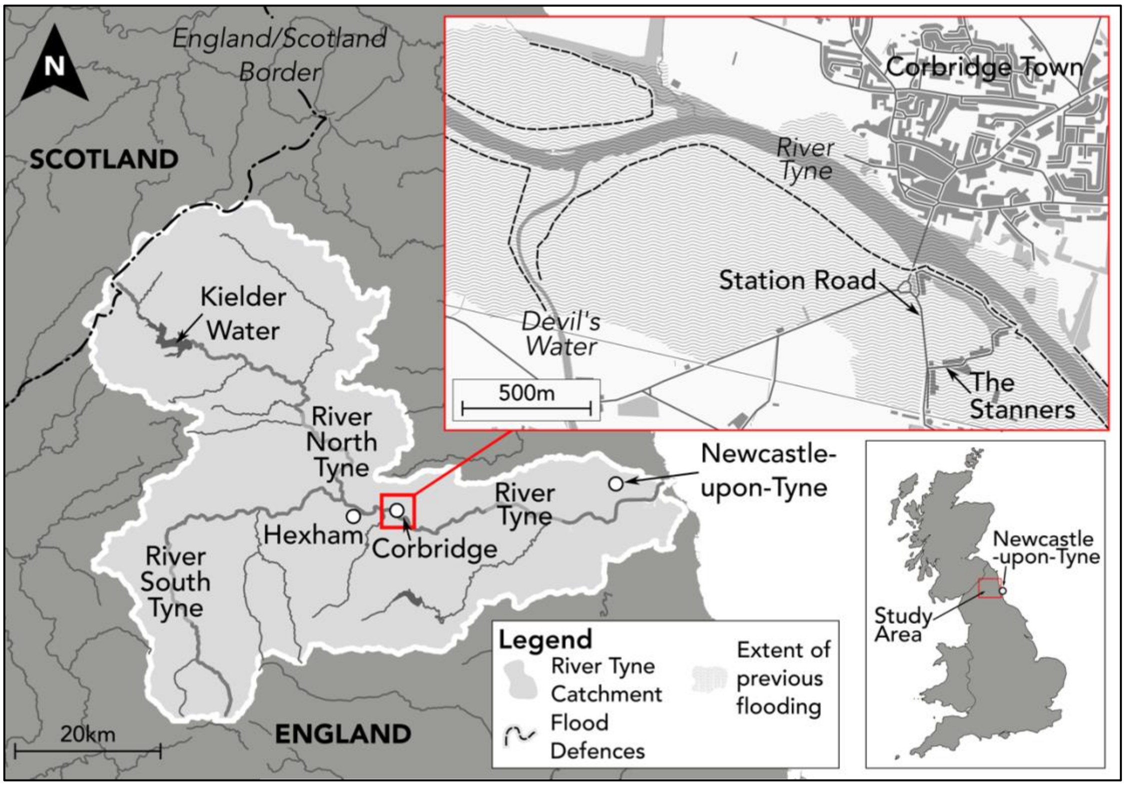


Figure 4-2. The River Tyne catchment and Corbridge study area. The inset highlights the extent of the area considered during the research.

4.4.2 The Research Approach

In the summer of 2016, we undertook research to explore local knowledge about flooding in the Tyne Valley based on working together with local people to develop new approaches to communicating risk. Our aim was to blend academic research expertise with the experiences of Corbridge residents to reimagine what flood risk information could be communicated and how it might be best presented. Figure 4-3 shows the multi-methods participatory approach developed.

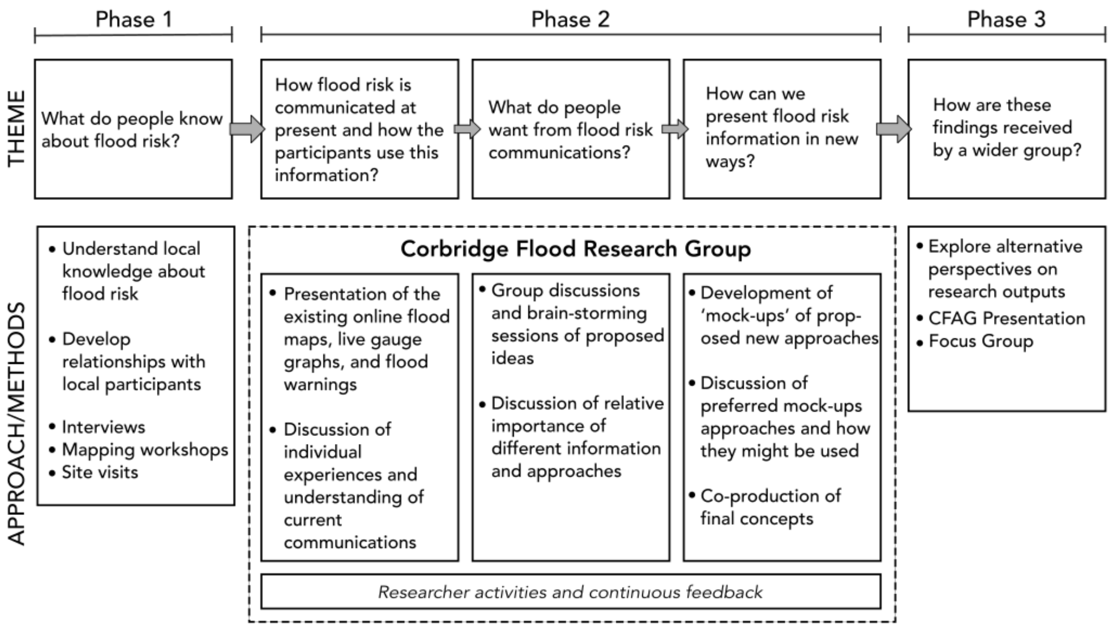


Figure 4-3. The multi-methods research process.

4.4.2.1 Understanding local knowledge and flood experience: workshops with the Corbridge Flood Action Group

In Phase 1 we conducted several group mapping and discussion workshops with members of the local Corbridge Flood Action Group (CFAG). The purpose of these meetings was to assess local knowledge and experiences of flood risk. Using a grounded theory approach, following Charmaz (2011), the material produced by these workshops, the maps, researchers notes, and the group discussions were integrated to identify key themes arising from the local experience of flooding. Using this approach we developed an understanding of the level of knowledge about, and engagement with, the flood risk problem, as well as developing a trusting relationship between the researchers and the CFAG.

4.4.2.2 Adopting a participatory approach to developing new flood risk communications: the Corbridge Flood Research Group

The relationship developed between the researchers and the CFAG during Phase 1 was instrumental in developing the Corbridge Flood Research Group (CFRG), which was developed through Phase 2 of the research. The CFRG was a group loosely modelled on the Environmental Competency Group used by Lane *et al.* (2011).

Similar to Lane *et al.* the CFRG was set apart from traditional focus or consultation groups by its focus on the practice of knowledge creation as a collaborative process and the integration of local 'non experts' into a practice of flood management usually carried out far removed from the local scale.

The CFRG consisted of six, self-selected members of the wider CFAG who had personal experiences of (five members), or interest in (one member), flooding at Corbridge. One of the researchers (Rollason), also took an active role in the group as a member, as opposed to a more traditional role as facilitator or group leader. Local members of the group contributed their experiential knowledge of flooding and flood communication, whilst Rollason (as an academic specialist and former professional flood manager in industry), brought expert technical knowledge and experience. By blending these two perspectives, the group was able to consider both the CFRG's communication desires and the practicalities of what could be achieved.

CFRG meetings were framed specifically to explore flood risk communications. The group met three times; only the theme of the first, '*how flood risk is currently communicated?*' was pre-determined. Subsequent meetings were driven by the group discussions and were predominantly unstructured, with participants determining what should be discussed and how. Meetings were audio recorded and field notes taken. After each meeting key discussion points were summarised, notes circulated to the group; all members thus participated in the iterative and ongoing development of the narrative being developed. Analysis of the material was undertaken throughout the process by adopting a flexible, mixed-method approach, situated within the principles of grounded theory (Charmaz, 2011; Knigge and Cope, 2006), for identifying and linking key areas of discussion. The discussions held with the group during CFRG1 and 2 allowed Rollason to prepare a series of prototype interfaces for communication. The technical skills employed involved flood risk mapping using GIS software, and running two dimensional flood models to capture and present information. The prototypes were presented for group deliberation at CFRG3, with the group jointly choosing four concepts and then working together to produce a final, shared version which represented the agreed outputs from the group.

4.4.2.3 Testing the prototypes outside the CFRG

In the final stage of the research the prototypes were presented to a larger focus group consisting of eight members of CFAG (new to the research), Rollason and one original member of the CFRG. The design and purpose of the concepts were outlined and the focus group discussed what they thought of the ideas, how they might be used, and any alternative ideas. The key aspects of this discussion were recorded during the focus group. No further amendment of the concepts was deemed necessary following discussions.

4.5 Current flood risk communications – do current approaches meet users' needs?

4.5.1 Understanding local knowledge and experiences of flooding

The initial CFAG workshops and CFRG1 revealed that local participants had a wealth of experiential knowledge about flooding. Many also had an understanding of wider catchment processes developed through hobbies, such as fishing, or work. Despite this, few participants had expected the flooding to occur despite the receipt of an official flood warning (see Section 4.5.2), with many assuming that the recently completed flood defences would protect them, as one participant stated:

> "*To be honest I didn't really believe it, because we had such faith in the flood defences that I actually didn't think we'd flood*" (Participant GW44)

Based on this commonly held belief, several participants made the decision not to evacuate, even when contacted by the emergency services (Oliver, 2016). That participants were surprised by the flooding, and unsure of how to react to it, demonstrates that flood communications had not developed the resilience of the Corbridge community to respond to flooding post the 2005 flood. These findings highlighted the need to examine in more detail how current flood risk communications were used by participants and how they might be redesigned to better develop resilience.

4.5.2 Reflections on current methods of flood risk communication

The CFRG members were familiar with the principle communications provided by the EA and several had used them before the 2015 flood. Table 4-3 summarises the group's attitudes towards the current flood communications and these are expanded upon below.

The CFRG felt that current approaches did not provide them with enough information to understand their flood risk or make an informed decision of what to do when they received a flood warning. In the case of the passive communications, the simple presentation of a flood risk extent, lacking any information on how floods occur, provided them with no information that they could actually use to understand what the stated flood risk meant. Participants stated they only used these maps for buying their homes or negotiating insurance; other than this participants thought that the maps told them nothing that they didn't know already:

> "*For me, I know I'm in a high risk area so all it* [the flood map] *would tell me is what I know already*" (Participant GW44)

Some participants also expressed a lack of trust in how the maps had been produced, as one participant explained:

> "*Originally, when they did the first online extreme flood map they drew the lines through the centre of the church* […]*, and I said "if it's getting to that level, it's coming down my chimney""* (Participant AK97)

The church at Corbridge sits approximately 16m above the floodplain. The group member still linked this experience and his distrust of those original maps to the current flood maps which appear superficially the same. The advancements in modelling and data since the production of the early maps are not evident in the way the maps are communicated, and information on how they are actually produced is not publicly available.

Table 4-3. Summary of the CFRG perspectives on existing flood risk communications. Members classified the approaches into 'passive' (the static, online flood maps) and 'active' communications (the live river level gauges and flood warnings) during the group discussion held during CFRG1.

Communication Type	**What the group thought about current approaches**	**What the group wanted from a future approach**
Active Communications • Live gauges • Flood warnings	- Useful but lacking in explanatory context and therefore difficult to interpret. - A lack of future prediction makes it difficult for people to know when and how to respond to a potential flood.	- Forecast water levels. - Forecast of how serious a flood is likely to be. - Water level information viewable at a catchment scale.
Passive Communications • All non-live flood maps	- Too simplistic to be of any use except when buying a house. - Complex probabilistic language is difficult to interpret or place in context.	- Detailed impacts on individual properties. - Integration of active and passive communications. - Communication of flood dynamics and timings rather than just extents to provide explanatory context.

Participants were much more engaged with the active communications, particularly the online availability of real-time river levels. Several CFRG members noted that they watched gauges upstream of Corbridge to try and judge how river levels might change at Corbridge in the near future. However, all participants expressed frustration with the lack of forecast river levels, which did not allow them to judge when flooding might occur, or how severe flooding of their homes might be in comparison to past events. This was a particular problem when participants received flood alerts, preliminary warnings that flooding **might** occur in the near future. These alerts, issued some time before formal flood warnings, are intended to prompt people to begin monitoring local river levels and prepare to take protective action. However, participants felt that the lack of forecast information left them unable to judge what to do and when.

Fundamentally, participants felt that the information they were being provided currently told them when to act but did not provide them with enough information to judge what it was feasible for them to do, or to what extent they should take action. As one participant noted regarding the 2015 floods:

> "*When we put things up high, not thinking that when the river comes over the water was going to be so high it would upend all those things, so everything I put up high to save we lost*" (Participant GW44)

4.5.3 What information do users want in flood communications?

CFRG2 focused on the information that people actually wanted from flood communications to allow them to understand their risk and take action, setting aside for the moment the practicalities of whether or not such information could be provided. The discussions reflected their initial criticisms of existing communications, focusing particularly on understanding the severity of the risk, and therefore what degree of action they could and should take (Table 4-3). Ultimately, group members wanted flood levels to be forecast, and a specific linkage between what these flood levels meant for their properties and what they could do in response, for example how high they needed to lift valuables:

> "*What you need is the starkest information,* […] *this level* [in the river] *means that level* [on the floodplain]*, means this amount of water in your house*" (Participant MJ33)

"*I want to know* […] *if it's that high, I'm going to do this, if it's going to be like 2005, I need to do that, because that was much less flooding*" (Participant GW44)

These discussions encompassed both passive and active communications, with participants generally agreeing that active communications, such as the river level graphs, should be more specifically linked to the passive communications, which could provide more in-depth and detailed information on property level impacts.

Some group members were concerned that providing more complex information would be confusing and potentially undermine responses to flooding. As a result, the group discussed how it was necessary to communicate flooding dynamics, for example how, when, and where flooding might occur, in order to be able to effectively interpret local flood risk. Participants referred to this type of information as contextual information, examples of which included where and when flood defences might be overtopped and how flood water might flow across the floodplain in order to flood their properties. This potentially reflects the relatively complex dynamics of the 2015 flood, where the principle areas of defence overtopping were out of sight of participants properties, and therefore flooding occurred from an unexpected direction.

4.6 Working together on new approaches to communicating flood risk

Between CFRG2 and 3 a series of draft prototypes of alternative passive and active flood risk communications were developed. Six prototypes were originally produced, exploring different types of information that could be communicated and different ways of communicating it (Table 4-4). Although the CFRG2 discussions had considered participants' information aspirations without considering the practicalities of implementing them, the group felt that it was important, in producing the prototypes, to consider how these ideas might be implemented in practice. Thus, where possible, proposals draw inspiration from existing examples of flood risk communications in other countries, proposed methods drawn from the literature, or examples of communications drawn from other fields (Table 4-4).

The prototypes were the focus of CFRG3. From the suite of initial concepts developed, the group considered four to be particularly useful (Figure 4-4). These four were considered by the local participants to give them the information they felt they needed to understand the risk of flooding, but also to make informed decisions about what action to take, and when, for future floods. These four prototypes were further developed by the group during and after CFRG3 and those shown in Figure 4-4 represent the final, agreed outputs from the group.

The four prototypes adopted by the group reflect the CFRGs two core desires:

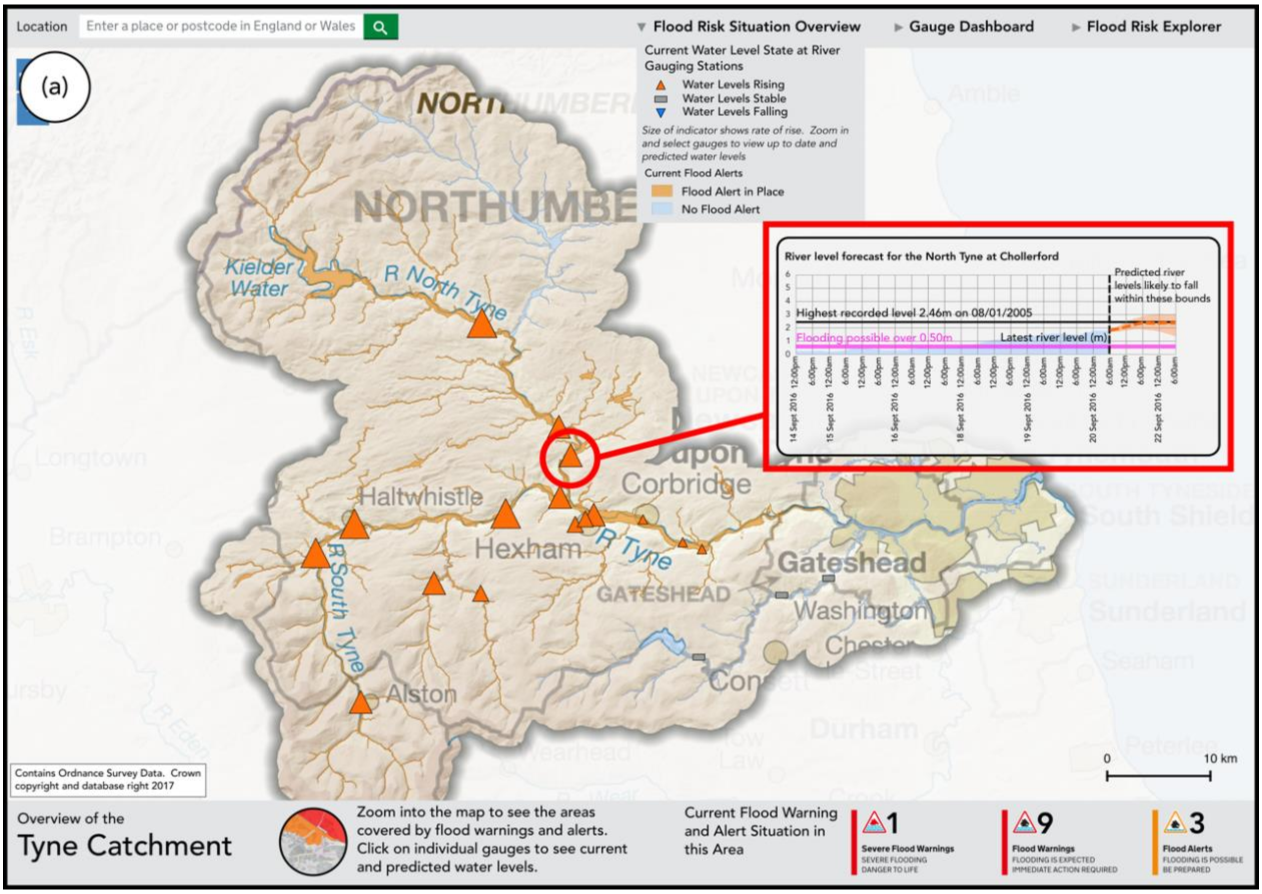
1. to be able to take responsibility for effectively monitoring their flood risk and judge, through forecast information, how significant any flooding might be (4-4a and b).
2. to have a detailed understanding of how flooding might occur based on a knowledge of past flooding dynamics (Figure 4-4c) and to be able to link forecast flooding information with the potential impacts on their own properties, allowing them to judge what action they could take in response.

Table 4-4. Summary of the initial prototypes for new passive and active flood communications produced between CFRG2 and 3 to communicate flood risk in different ways.

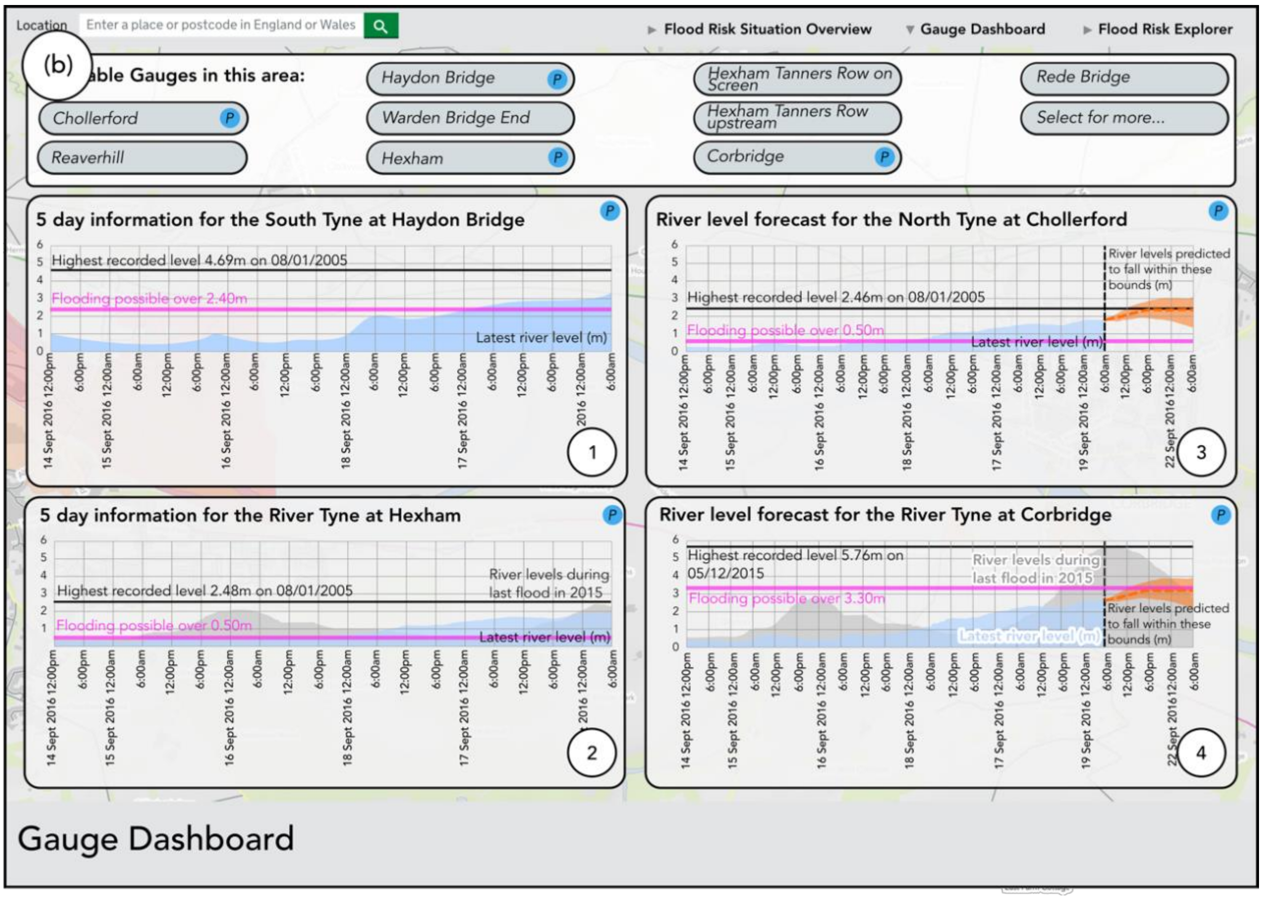
Mock-up		Focus of the approach	Sources of inspiration
1a	Catchment-wide gauge map	Shows the status of river gauges across the Tyne catchment indicating current status and rate of change of status where applicable.	Fishpal website (Fishpal.com, n.d.).
1b	Catchment-wide gauge map, zoomed in example	Shows current flood warnings and status of gauges in a zoomed in fashion.	Existing flood communications maps and researcher experience.
2	Gauge graph examples dashboard	Shows multiple gauges in a single 'dashboard'. Gauges display different options: 1. Current approach 2. Current approach with historical hydrograph overlay 3. Current approach with future water level prediction 4. Current approach with both (2) and (3).	Proposed alternative approaches were based on 1. Current display options 2. With research interpretation of CFRG suggestions 3. Proposed prediction options from Leedal et al. (2012).
3a	Flood Impacts Explorer – flood depths	Shows modelled flood depths from a previous flood event (2016).	Existing flood depth maps and researcher experience.

Mock-up		Focus of the approach	Sources of inspiration
3b	Flood Impacts Explorer – flood pathways	Shows modelled flood depths and explanatory context of key flood pathways and timings. Shows linked flood hydrograph indicating water levels at which key mechanisms become active.	Flood depth maps and from researcher interpretation of key information requested by the CFRG members.
3c	Flood Impacts Explorer – historical frequency	Shows modelled flood depths with indication of historical frequency of flooding events of given magnitude.	USGS Flood Inundation Mapper 'Historical Flooding' information.
3d	Flood Levels Explorer – potential water levels	Shows user variable water level indicator, demonstrating potential flood extent and depth at different gauged water levels. Could be based on either local assessment of a digital elevation model, or a model outputs library (For example see Hogan Carr et al., 2016).	USGS Flood Inundation Mapper 'Flood Inundation Map Library' (Hogan Carr et al., 2016; United States Geological Survey, 2016).

*Figure 4-4. Flood risk communication concepts adopted by the CFRG (concept numbers relate to details in Table 4). **(a)** CFRG Concept 1a showing the catchment-wide overview of the river gauging station status. **(b)** CFRG Concept 2 showing a proposed gauge dashboard allowing users to 'pin' multiple gauges of their choice into a single place for rapid review of how river levels upstream are responding to rainfall. **(c)** CFRG Concept 3b outlining a detailed assessment of historical flood dynamics (in this case the December 2016 flood event). **(d)** CFRG Concept 3d shows a user-selected water from the Corbridge gauge and displays the corresponding extent and depth of flooding based on simple water level interpolation.*

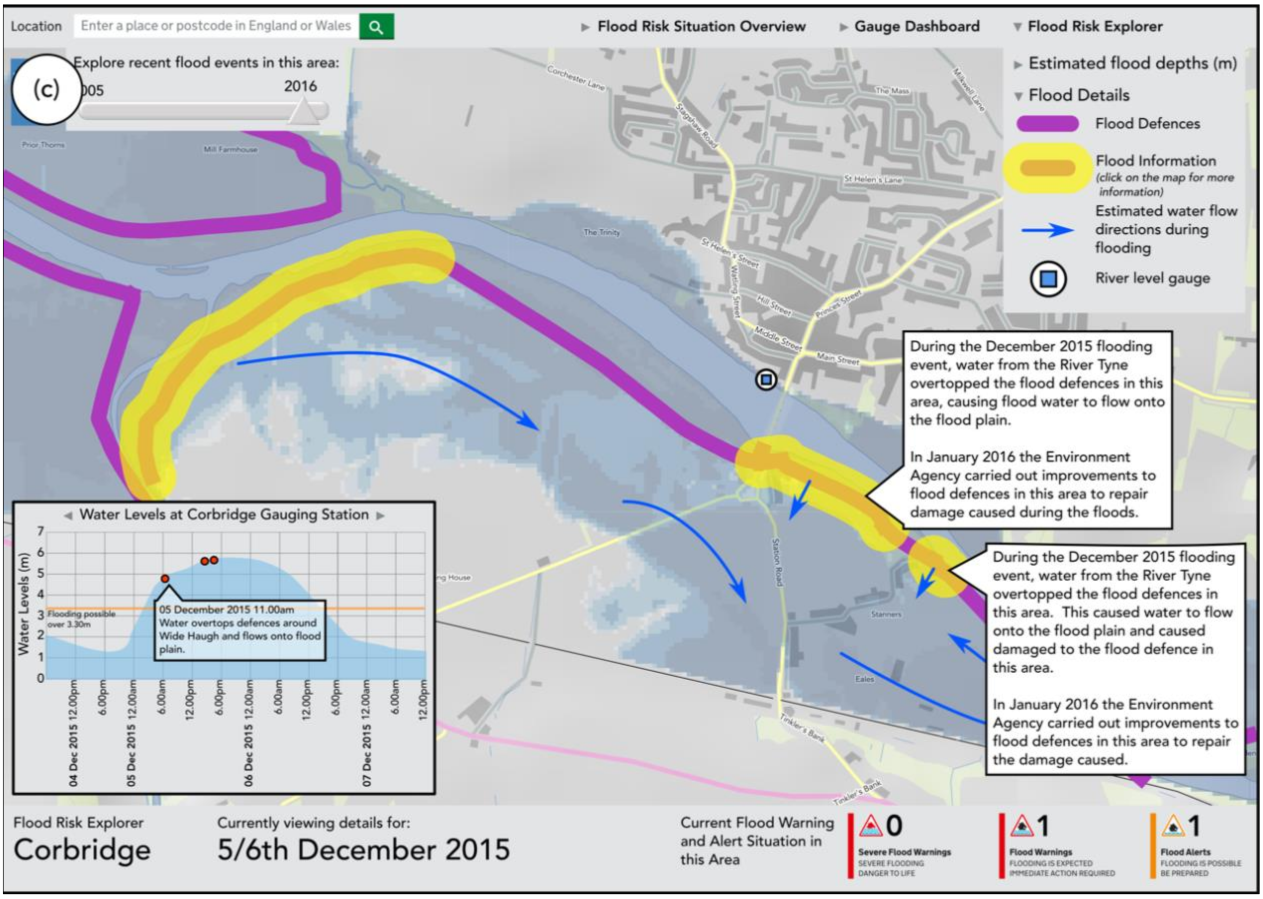


Location
Enter a place or postcode in England or Wales
Flood Risk Situation Overview
Gauge Dashboard
Flood Risk Explorer
(a)
Current Water Level State at River Gauging Stations
Water Levels Rising
Water Levels Stable
Water Levels Falling
Size of indicator shows rate of rise. Zoom in and select gauges to view up to date and predicted water levels
Current Flood Alerts
Flood Alert in Place
No Flood Alert
River level forecast for the North Tyne at Chollerford
Predicted river levels likely to fall within these bounds
Highest recorded level 2.46m on 08/01/2005
Flooding possible over 0.50m
Latest river level (m)
NORTHUMBERLAND
Kielder Water
R North Tyne
Haltwhistle
Hexham
Corbridge
R Tyne
R South Tyne
Alston
Gateshead
GATESHEAD
Washington
Chester
Consett
Contains Ordnance Survey Data. Crown copyright and database right 2017
0
10 km
Overview of the
Tyne Catchment
Zoom into the map to see the areas covered by flood warnings and alerts. Click on individual gauges to see current and predicted water levels.
Current Flood Warning and Alert Situation in this Area
1
Severe Flood Warnings
9
Flood Warnings
3
Flood Alerts



Location
Enter a place or postcode in England or Wales
Flood Risk Situation Overview
Gauge Dashboard
Flood Risk Explorer
(b)
able Gauges in this area:
Haydon Bridge
Hexham Tanners Row on Screen
Rede Bridge
Chollerford
Warden Bridge End
Hexham Tanners Row upstream
Select for more...
Reaverhill
Hexham
Corbridge
5 day information for the South Tyne at Haydon Bridge
Highest recorded level 4.69m on 08/01/2005
Flooding possible over 2.40m
Latest river level (m)
River level forecast for the North Tyne at Chollerford
River levels predicted to fall within these bounds (m)
Highest recorded level 2.46m on 08/01/2005
Flooding possible over 0.50m
Latest river level (m)
5 day information for the River Tyne at Hexham
River levels during last flood in 2015
Highest recorded level 2.48m on 08/01/2005
Flooding possible over 0.50m
Latest river level (m)
River level forecast for the River Tyne at Corbridge
Highest recorded level 5.76m on 05/12/2015
River levels during last flood in 2015
Flooding possible over 3.30m
River levels predicted to fall within these bounds (m)
Latest river level (m)
1
2
3
4
Gauge Dashboard

[Figure 4-4 continued]



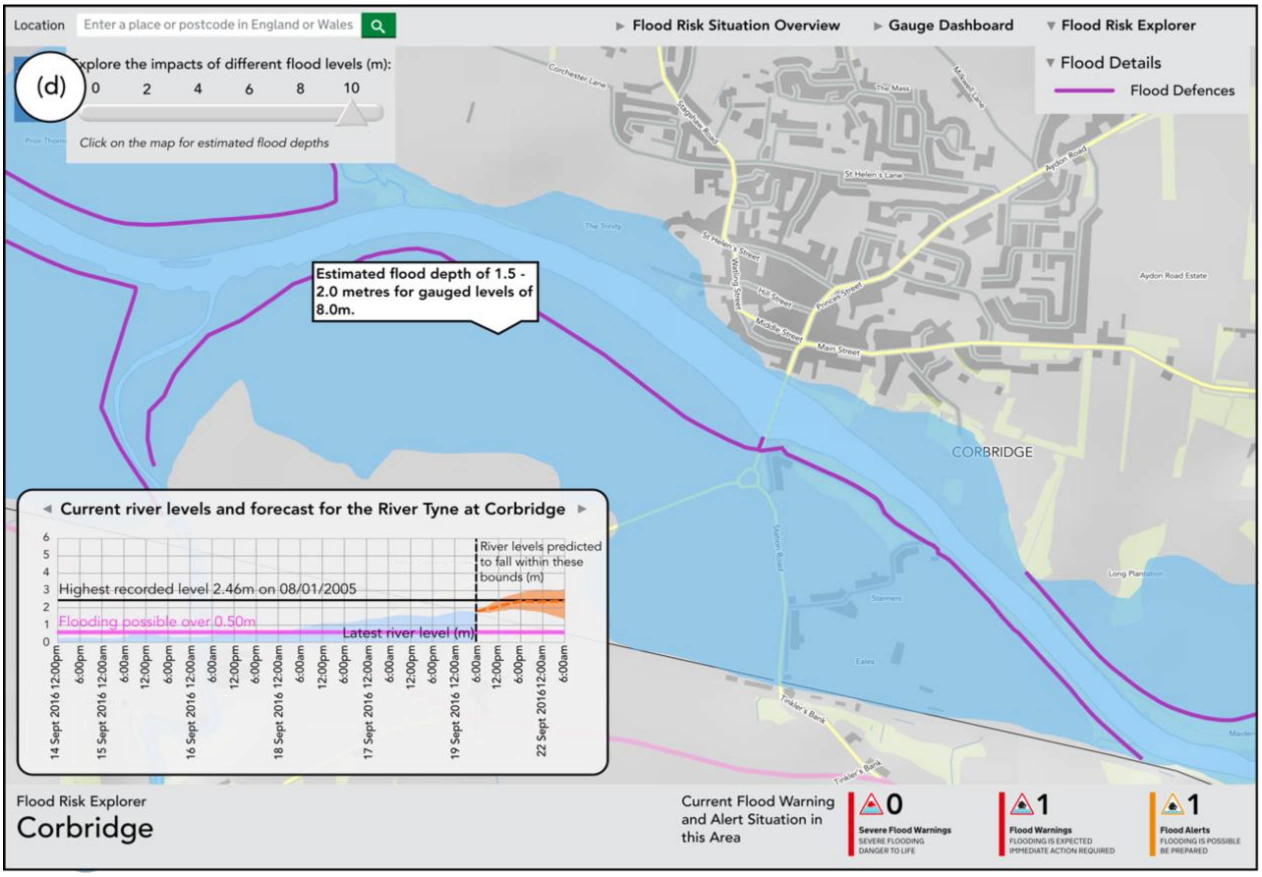


Figure 4-4a shows the catchment-wide overview of the river gauging station status, enabling users to quickly assess how the catchment is responding to rainfall. This prototype map is linked specifically to individual gauge records allowing users to select and explore specific sites in more detail. Inspired by the online angling tool 'Fishpal' (Fishpal.com, n.d.) used by one of the CFRG participants, the group members felt this tool allowed them to easily monitor catchment-scale river response, using their knowledge of how rainfall in different areas of the catchment translated into flood risk at Corbridge.

Figure 4-4b outlines a prototype gauge *dashboard* which allows users to 'pin' multiple gauges of their choice into a single place for rapid review of how river levels upstream are responding to rainfall. This prototype answers group members annoyance with only being able to view one gauge at a time using the current system. This prototype also reflects different options for how gauged levels should be displayed which were also discussed by the CFRG: (1) Current approach adopted by the Environment Agency; (2) Current approach with an overlay comparing current levels with a historical hydrograph; (3) Current approach future water levels predicted based on the method proposed by Leedal *et al.* (2013), or; (4) Current approach with both (2) and (3). CFRG participants felt that forecast water levels (as in 3) allowed them to plan protective actions in advance of flooding occurring by anticipating when they would need to take certain actions, whilst historical comparisons (such as that shown in 2) allowed them to contextualise the significance of predictions and therefore judge what level of protective action was necessary.

Figure 4-4c presents a detailed assessment of historical flood dynamics (in this case the December 2015 flood event). In this prototype users would be able to select different elements to be provided with a detailed account of how flooding occurred and what action might have been taken in response. The hydrograph allows users to identify water levels at which different flooding mechanisms begin to operate. CFRG members felt this map developed their understanding of how flooding occurred and when, allowing them to understand the significance of local gauged river levels.

Figure 4-4d shows the simulated extent and depth of potential flooding based on a user-selected water level for the Corbridge gauge. This prototype was inspired by the United States Geological Survey 'Flood Inundation Map Library' (United States Geological Survey, 2016). Current and predicted water levels at Corbridge are displayed on the gauge display to allow users to link current and predicted water levels with their evaluation of potential impacts. CFRG participants felt this simple linkage between river levels and potential floodplain impacts was important for correctly interpreting what forecast river levels might mean, and for demonstrating what degree of protective action was needed in different situations.

4.7 Scaling up: testing the prototypes with the wider Corbridge Flood Action Group

The four updated prototypes were presented to the wider CFAG at a group meeting and also at a smaller focus group. The prototypes were well received by the focus group (Table 4-5), with the underlying themes of understanding flood dynamics, flood impacts, and future prediction being reflected in the discussions. All participants saw the potential for the active communications to enable them to take action to reduce the impact of future floods.

The prototype in Figure 4-4c provoked a different response to that of the CFRG. The focus group members thought that this map was not for them to use in preparing for flooding, but instead was as a tool for them to use to engage more effectively with the EA about ongoing FRM on a more even information footing:

> "*I think that information is important for us to see, so that we can have intelligent conversations with the Environment Agency*" (focus group participant)

Instead, to prepare for a flood in the near future, the focus group participants preferred the simple water level model shown in Figure 4-4d.

This discussion highlights the complex interactions between individual users and the different approaches to communicating flood risk and the difficulties of presenting only a small variety of information in order to represent a complex and dynamic threat such as flooding.

Table 4-5. Responses to the CFRG mock-ups from the Corbridge Flood Action Group Focus Group (CFRG mock-up numbers refer to Table 4-4).

CFRG Mock-up	Summary of Flood Group Focus Group Responses
1a Gauges Overview	• Very useful for understanding the overall view of the catchment • Can look at the whole river all at once and can be used to understand how large a flood might be • Would need to be able to understand what the information meant for flood impacts at Corbridge • Would like to see predictors of water level increases on the overview map
2 Gauge Dashboard	• Predicted and historical information both useful in indicating potential magnitude and also providing context for understanding what levels mean • Don't consider (4) to be too complex • Would like an indication of key trigger points, for example level at which defence overtopping begins • Uncertainty very important in predictions of water levels to avoid users minimising future warnings
3b Flood Explorer, pathways and timings	• Provides a vivid contextual understanding of what occurred during previous floods • Not necessary or interpreting current or future events, gauged, real-time information much better for this • Much more useful for engaging with the EA regarding flood management activities
3d Flood Explorer, user simulated flood depths	• Very useful for understanding flood impacts and allowing users to link gauged information with potential flood depths • More useful than the historical pathways and timings idea

4.8 Discussion

In this section we bring together the experience of the CFRG experiment with theories of risk communication. We argue that participation such as that demonstrated by the CFRG must play a role in developing future flood communications, especially in light of the shift from flood defence to flood management and the resulting distribution of FRM responsibilities onto those at-risk (Butler and Pidgeon, 2011). Such involvement will enable responsible agencies to better communicate flood risk in new ways, empowering those at-risk to apply their local knowledge and experience to improve their resilience in the face of flood events.

4.8.1 Implications for current flood risk communications

The research undertaken has shown that there are severe limitations to current flood risk communication approaches which prioritise simple threat messages. The PMT model (Rogers, 1975) can be used to analyse the responses of the CFRG to the existing flood communications and their desire for alternative approaches, focusing particularly on the ideas of the threat and coping appraisal (Grothmann and Reusswig, 2006). The CFRG saw no useful information in the existing passive maps which suggests that this approach does not support the development of threat appraisal. The lack of information on flood dynamics also provides no basis on which users can judge for themselves how communicated risk information might translate into an impact on their own property. In this context, threat appraisal is reliant on previous experiences, whether personal or vicarious. In the Corbridge context this wholly underestimated the threat, resulting in a non-protective response based on ‘wishful thinking’ regarding the recently completed flood defence works. Hopkins and Warburton (2015) refer to this paradox as the ‘prison of experience’, in which infrequent or unrepresentative events imprint themselves into subjective knowledge as representative experiences to be drawn on in the future. CFRG participants desire for detailed information on past local flooding characteristics or the simple flood depth simulator, can be seen as an attempt to place their experiences in a wider context, breaking out of the 'prison of experience' and establishing a more holistic understanding.

Both the passive and active communications assessments also suggest a failure of current approaches to establish a meaningful coping appraisal, particularly in relation to the judgement of how much time participants in this study had to react and what degree of action they should, or could, take. Several participants expressed surprise at the prototype flood map showing flood dynamics, which highlighted overtopping of upstream defences approximately four hours prior to property flooding occurring. These participants had no understanding from the current flood maps (which do not show information such as areas of potential overtopping) that flooding might either be inevitable or occurring, or that they potentially had several hours in which to prepare or act. Neither were participants able to accurately judge the degree to which they should prepare based on the live gauged information, since this online information does not currently offer information on predicted water levels. This led to negative coping appraisals and the adoption of non-protective behaviours, where participants either ignored what might be happening or took ineffective action. In this context, the Group's desire to see whole-catchment scale information, which incorporates future predictions, can be seen as building not just their personal appraisal of the threat, but also their coping appraisal. Understanding the threat allows them to feel in control of their own flood risk situation and to make their own decisions, rather than reacting blindly to flood warnings; a situation that participants said left them very stressed and uncertain.

4.8.2 Future flood risk communications: participation as a vehicle for developing resilience through flood literacy

Viewed in the context of the PMT, current flood risk communications could therefore be judged to be counter-productive; they attempt to provoke a heightened perception of flood risk, without providing the information required by users to establish strong, positive threat **and** coping appraisals. Without developing coping appraisals, users adopt the kinds of non-protective behaviours proposed by Bubeck *et al.* (2012), ignoring, rejecting or misinterpreting official risk information to make them **feel** more secure in the face of extreme uncertainty (Harries, 2008). These behaviours reduce community resilience by increasing the shock of events when they occur unexpectedly or do not match individuals previous experiences; increase individual hazard through refusals to evacuate; or foster learned helplessness when believed protective behaviours fail or have no effect.

To encourage positive threat and coping appraisals future flood communications need to move away from the simplistic flood threat messages that are currently cascaded to people at-risk. Instead, and as the four prototypes created here demonstrate, communications should provide more detailed, holistic hazard information. This type of information, rather than relying on raising risk perception alone, seeks to develop a local 'flood literacy' by fostering local knowledge about flooding. Flood literacy repositions those at-risk as active agents in managing local flood risk, able to make their own judgements and decisions on risk and protective behaviour, rather relying on expert knowledge (Willis et al., 2011). By empowering people in this way, flood literacy develops local resilience in a way in which simple, threat-based communications cannot: it provides at-risk individuals and communities with the information necessary to (i) assess their personal level of risk and how they might be affected, (ii) determine when a flood might be about to occur and how it might affect them, and (iii) determine appropriate actions by which they might mitigate potential flood impacts.

To encourage effective flood literacy through improved flood risk communications, there is a need to re-establish resilience as a process grounded in relationships, social learning and dialogue (Benson et al., 2016; Twigger-Ross et al., 2014, 2011), rather than 'hard' infrastructure or property (McBain et al., 2010). Participatory approaches offer a potential avenue through which the reinvigoration of resilience in this fashion might occur. The results of our research demonstrate the importance of working together with end-users in developing new solutions to flood risk problems, similar to findings of previous participatory research (Bracken et al., 2016; Landström et al., 2011; Lane et al., 2011b; Whitman et al., 2015). The practices of participatory working help to unify local and official perspectives on flood risk, and develop local capacity to understand and take action (Pain, 2004) in ways that established approaches to communication have been shown not to be able to achieve.

4.9 Conclusions

The last three decades have seen rapid changes in our approaches to addressing flood risk, and a professional acceptance that flooding cannot be prevented and must instead be managed. Societal resilience to floods has emerged as a key pillar of this new approach to 'living with floods'. Changes in policy have increasingly focused on the resilience of critical infrastructure, and developing community resilience has increasingly been undertaken through an educational model of risk communication. However research suggests that this approach is failing to develop individual and community capacities for understanding and responding to floods in a resilient manner.

The research presented here has demonstrated the application of participatory approaches to explore the linkage between flood risk communication, individual behaviour, and generating resilience. We have worked together with a competency group drawn from a flood-affected community to understand how they use and interpret current flood risk communications, what information is important to them in understanding and responding to floods in a resilient manner and how could information be better communicated. Our conclusions are as follows:

1. Current approaches to flood risk communications fail to meet user needs in understanding flood risk or allowing personal judgements of how and when to act. Through a reliance on communicating simple, threat-based messages rather than developing in-depth understanding, current communications heighten threat appraisal but diminish coping appraisal. This promotes non-protective behaviours, either through wishful thinking and over-reliance on management organisations, or through denial and learned helplessness.
2. Users desire a greater range of information about floods, including locally specific information on flood dynamics, which would allow them to understand their personal flood risk situation and how floods will affect them.

Delivering this information is vital to enable those at-risk to judge what protective actions they can take, and when they should take action. Our results demonstrate that users desire forecast information beyond what is provided currently. Without forecasts of river levels or flood extents, users are unable to judge the potential severity of future flooding, which means they are reluctant or unwilling to take action blindly.

3. There are a great variety of different perspectives on how flood risk should be communicated and the purpose of these communications, even within a small area. The complexity of the risk message-behaviour interface means that one message cannot be tailored to all perspectives. We propose a communications model which is instead focused on the development of 'flood literacy', where communities and individuals are empowered to develop their own knowledge about local flood risk and how they can act to manage it.
4. Flood literacy can reinvigorate flood communications as a tool for developing flood resilience by establishing flood communications as a two-way dialogue focused on the development of shared, locally grounded knowledge. Participatory working approaches represent a vehicle through which communications and resilience can be linked. Resilience and participation are both grounded in the principles of trust, the development of relationships, and the co-production of knowledge and solutions. Participation therefore has the potential to offer a solution, to re-imagine our approaches to communication, integrate alternative perspectives, and place risk communications users, traditionally considered only as 'knowledge consumers', at the heart of the process of creating future communications approaches.
5. We propose four co-produced prototype user interfaces which can deliver the information needed to help those at-risk develop flood literacy.

The challenge of quantifying how new and innovative modes of knowledge creation, communications, and relationship-building can provide valuable opportunities for bettering flood risk management remains. However, the approaches described here have important implications for how we communicate flood risk, and how we work alongside those living with risk to develop more flood-resilient communities.

[Page Left Intentionally Blank]

Chapter 5 Discussion

This Chapter draws together and summarises the key findings presented in chapters 2-4, addressing the original research aim by exploring existing participatory practices in current hydrological catchment management, and designing new approaches, to help understand how we can best integrate alternative knowledges and perspectives. It then moves on examine how we might better manage catchments and develop more resilient communities in the future. In so doing, I look to re-examine the original premise of the thesis laid out in Chapter 1, arguing that some of the initial assumptions behind the research need to be reconsidered in light of the findings published in the academic literature (Chapters 2 to 4). In turn this necessitates a new model for considering catchment management, participation, and resilience which I outline and discuss in detail below.

5.1 Key research findings

5.1.1 The nature of participation in catchment management

Chapter 2 explored the nature of participation in catchment management, particularly following the shift towards Integrated Catchment Management (ICM) approaches supposedly embedded in overarching policy frameworks such as the EU Water Framework Directive 2000 (WFD) and the UK Catchment Based Approach (CaBA). These policy drivers ostensibly embed the concept of active public participation into the management of the water environment at the catchment and sub-catchment scale, facilitated by catchment partnerships aimed at bringing together traditionally disparate management agencies. However, the results of the research suggest that this is not in fact successful in practice at the local level. As Chapter 2 showed by exploring the practices of management of the Greening the Twizell Partnership, drivers of management operating at the supra-catchment scale dictate the practices of management demonstrated during the research. The translation of these supra-catchment drivers to local scale practices entrenches existing top-down management approaches. Participation was characterised by a low-power-low-representation format, where communities were excluded completely from participating in management practices, or a low-power-formal-representation model, where participation was through rigidly controlled consultation exercises (Plummer and FitzGibbon, 2004). These results were in contrast to an engaged and informed network of local participants who demonstrated an emerging aspiration for deeper participation and local control. These results support findings from elsewhere in England, where Cook *et al.* (2013b) found existing management structures obstructing the ability of catchment organisations to fully exploit participatory democracy at the local level.

As a result of these findings, Chapter 2 argued for: (i) the established governance structures which maintain normative top-down management approaches to be restructured in order to more meaningfully incorporate active participation, and (ii) for future research to demonstrate how participatory practices could be used to enhance and extend existing practices of knowledge creation and build new practices grounded in shared knowledge and social learning. Working towards the development of more flexible, participatory governance structures, and demonstrating more effective use of alternative perspectives is important in developing management approaches which can address future challenges such as climate change, which have the potential to generate significant, but spatially and temporally disparate, social and environmental upheaval.

5.1.2 Using local knowledge to enhance existing practices of knowledge creation

Building upon the findings of the research presented in Chapter 2, Chapter 3 presented a new methodology for the validation of flood inundation models, incorporating local knowledge collected through participatory research with a flood affected community. Flood Inundation Modelling (FIM) is a key aspect of Flood Risk Management (FRM), used to inform activities such as spatial planning, the design and construction of flood defences, and also the risk information communicated to the public. Despite this public facing aspect of flood risk management, FIM is predominantly an expert-led practice, using scientific data such as river gauge levels, and remotely sensed data to reconstruct the complex dynamics of two dimensional floodplain flow. However, this data is often unable to fully demonstrate how effectively models are simulating this complex behaviour, often focusing on temporally or spatially discrete validations, such as maximum flooded extent or peak discharge. This information can provide a global understanding of model performance but may miss local spatial and temporal variability in model performance, with potentially significant implications if models are used for local disaster planning such as evacuation planning.

Using Volunteered Geographic Data (VGI) collected from a flood affected community, the research proposed a new method for the validation of flood inundation models to extend and enhance traditional, statistical approaches. Using qualitative and semi-qualitative data, such as participant testimony and photographs taken opportunistically during a flood event, the method examines flooding pathways, the event timeline, and local variability in impacts. Utilising non-standard data through this new method, the research demonstrates how the validation of models can be enhanced to ensure they effectively represent the ways in which flood affected communities experience flooding. This enhances our existing practices of FIM through the creation of new, shared knowledge on flood risk, bringing together two often competing perspectives; that of expert flood modellers, that of flood affected local people.

5.1.3 Building new practices of knowledge creation in Flood Risk Management

The idea of uniting competing perspectives of FRM is extended further in Chapter 4, where the research explored how participation could be effectively embedded into new FRM practice. Like everyday catchment management, participation is a central feature of FRM. In contrast to everyday management, this participatory shift reflects a realisation that traditional 'flood defence' approaches are no longer sustainable. Instead, practices focus on the management of flooding impacts as and when floods occur. Flood-affected communities are therefore a key focus of FRM work with the development of 'community resilience', defined as the ability to withstand and recover from floods, a core management objective. However, as the research presented in Chapter 4 showed, practices of participation in FRM are similarly top-down to those adopted in everyday management. Top-down, simplified communications are intended to instil fear and a heightened threat appraisal, persuading at-risk individuals to adopt protective behaviours.

Working together with the flood-affected community at Corbridge, the research showed that this approach is not effective in building resilience, with participants unable to determine what action they should take or when, a situation which in some cases reduced their resilience through encouraging non-protective behaviours. Instead, the research demonstrated how adopting participatory practices can bring together and develop our understanding of different perspectives and lead to more effective and applicable knowledge. By adopting the model of the competency group, and bringing together expert academic knowledge and local experiential knowledge, the research was able to develop new approaches to risk communication which specifically work to build flood knowledge and resilience through developing a local 'flood literacy'. This practice of social learning generates new, shared knowledge and repositions at-risk people as partners in the management of flood risk.

5.2 Everyday and extreme event management: an unsustainable division between interconnected systems?

Brought together, the research shows that our current approach to participation and resilience in the management of the water environment is problematic. As reported in Chapter 2, although ICM approaches theoretically bring together the management of social and ecological systems at the catchment level (Lerner and Zheng, 2011), this aspiration is not demonstrated in practice. In the everyday management of catchments, people and the social system of the catchment are excluded from the 'integrated' management of the ecological catchment system (Figure 5-1a) and the everyday processes which are the focus of groups such as the Greening the Twizell Partnership. Instead, management of the ecological system is driven by top-down governance, translated through the expert-led practices of management agencies. The people and communities which represent the social system of the catchment are included in only a token fashion at specific moments in time and through certain mechanisms such as public consultation and are otherwise considered outside of the catchment system.

Extreme events are also not included within this system. As shown in Chapter 2, despite local flooding issues being present in the catchment and being a focus of local community interest, these were not a driver for the Greening the Twizell Partnership and were not considered during the planning of catchment interventions. Occasional and outside of the catchment system norm, these intermittent extremes are 'disruptors' of the normal cycle of catchment management (Lane et al., 2013). Although FRM is now framed through the concept of 'living with floods', with a focus on resilience, this resilience is centred on 'bounce-back' and a return to a normal, pre-event state, as was discussed in Chapter 1 (Davoudi, 2012). As Chapter 4 showed, the same top-down governance and participatory practices adopted in everyday management are applied to preparing for and responding to extreme events, relying on one way communication of risk information intended on raising threat appraisals and promoting resilient behaviours (Figure 5-1b). However, this focus on top-down communication of generalised risk knowledge means that, despite being expected to take a leading role in developing flood resilience, those at-risk are not meaningfully integrated into the practiced of FRM. Instead, they are expected to listen and obey expert-led pronouncements on adopting protective behaviours. As such they lack any meaningful power to contribute their own experiential knowledge of risk, or to influence the practices which determine how, why, or to what extent they are at-risk. This heavily asymmetrical relationship limits their role in resilience building to the bounce-back model of resilience discussed in Chapter 1. They lack any capacity to change this framing of resilience through long term adaptation. Instead, both resilience and participation in this conceptualisation as operational targets to be achieved. Integration of community knowledge and evidence would enable adaptive, evolutionary resilience, as proposed by Davoudi *et al.* (2013), to be supported in practice.

Considered together, these disconnected approaches to management produce an unsustainable dichotomy. On the one hand floods are part of the water environment, events to be 'lived with', and their effects need to be managed through developing resilience. On the other hand, this conceptualisation of resilience sees floods as aberrations which are not 'normal', cannot be managed through the everyday practices of management, and their impacts require a rapid recover to a normal state. The outcome of this conceptualisation of risk and resilience is little different to traditional flood defence approaches in attempting to avoid the impacts of flooding. Both paradigms of management can be seen to assume that ecological systems can be effectively managed and kept separate from social systems (Grove and Chandler, 2017). The modernist roots of the Resilience/ICM paradigm help to explain the limited nature of the participation demonstrated by the results presented in Chapters 2 and 4; although participation has been introduced as a high level driver, full participation cannot be implemented with this conceptualisation of ecological and social systems as this would require breaking down the barrier between these systems.

5.3 Collapsing the ecological - social system divide: resilience as a mechanism for truly integrated management?

The idea that flood defences could effectively separate people living on the floodplain from the impacts of flooding has been shown to be false by repeated major floods over the last three decades (Butler and Pidgeon, 2011). However, the new ICM/resilience paradigm demonstrated by this research built on established governance structures and assumptions is no more sustainable. It transfers the costs of FRM onto communities (White and O'Hare, 2014), whilst also trapping them into a cycle of flooding and recovery (Davoudi, 2014), without the powers to effectively take ownership of their risk or evolve to address it. In the face of changing flood hazard driven by climatic changes (Feyen et al., 2012; Hirabayashi et al., 2013), and increases in risk due to future socio-economic change (Mokrech et al., 2015), there is an urgent need to re-evaluate our conceptualisations of resilience and participation in the context of everyday and extreme event management.

As outlined in Chapter 1, researchers have already argued for a socially-grounded evolutionary resilience which embeds concepts of adaptability and transformation into institutional environmental management (Abdulkareem et al., 2018; Davoudi et al., 2013; for example Folke, 2006; Maclean et al., 2014; Walker and Cooper, 2011).

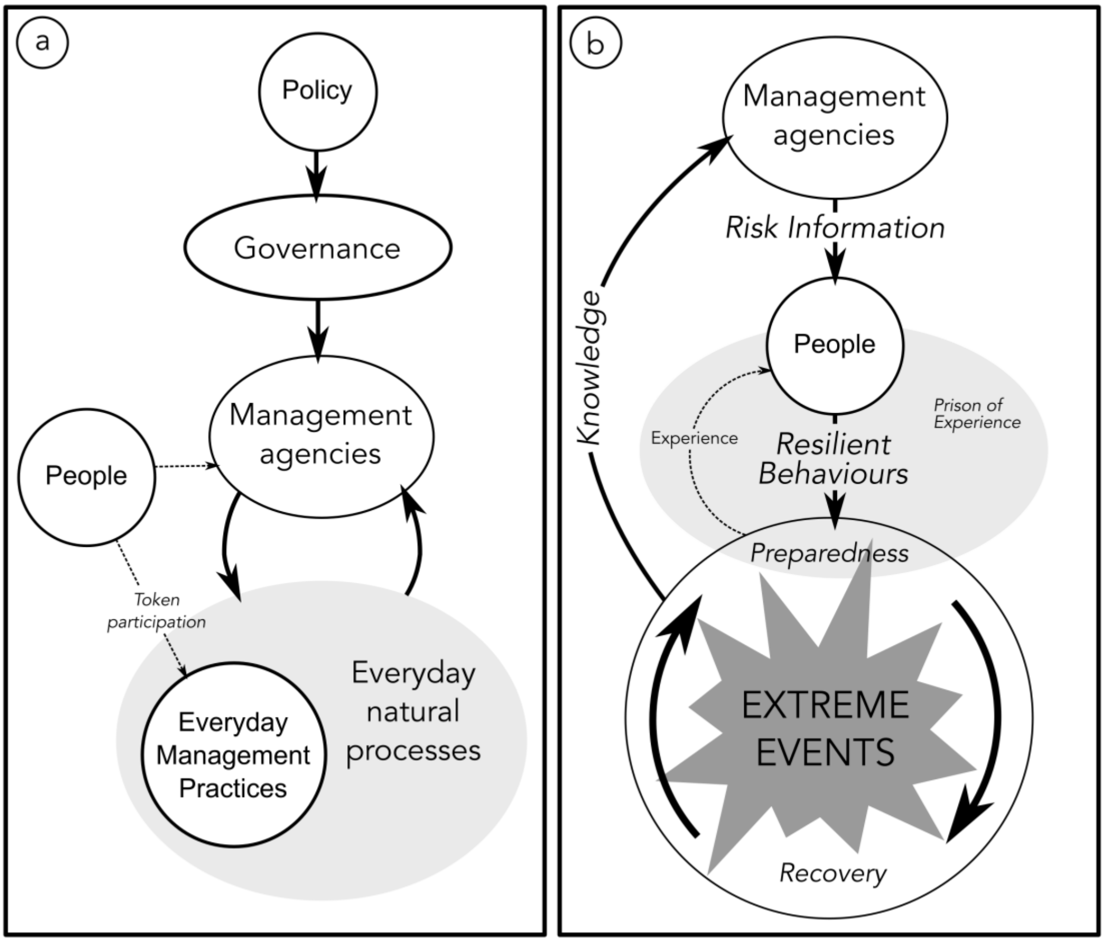


Figure 5-1. The existing frameworks of management in (a) the everyday management of catchments and (b) the management of extreme events. In the everyday management of catchments, people are predominantly excluded from management practices and only participate in the most token fashion. In the management of extreme events, which act as disruptors to the everyday management cycle, people take a central role as targets for the development of resilience through the adoption of resilient, protective behaviours. However, their relationship with management agencies is highly asymmetrical with the development of resilience predominantly being driven by the communication of top-down risk information. Flood-affected people have few opportunities to develop a meaningful understanding of their risk or what they can do about it, instead often being trapped by the prison of their own experience, often underestimating risk levels or assuming that there they can do nothing to cope with extreme events.

This has already begun to be brought together with integrated systems management ideas which influence ICM thinking, to consider how resilience might be embedded in management practice. Biggs *et al.* (2012) argue for seven underlining principles in developing resilience in socio-ecological systems: maintaining diversity; managing connectivity; managing feedbacks; fostering adaptive systems thinking; encouraging learning; broadening participation; and encouraging polycentric governance. Robinson (2012) also argues for resilience grounded in systems thinking, as well as the establishment of new societal and legal norms of management, and practices and procedures which embed learning and re-learning into everyday management. Similarly, Kareiva and Fuller (2016) propose a focus on continuous change and evolution: the adoption of experimentation and the use of novel practices; and the de-emphasis of rigid, top-down mandated practice and a focus instead on the achievement of outcomes through flexible practices. However, many of the principles proposed for developing resilience, such as broadening participation, (social) learning, or systems thinking, are already supposedly embedded into management policy. However, as this research has demonstrated this is not enough to overturn established management philosophies which are still wedded to historically dominant conceptualisations of participation and resilience. These conceptualisations see participation and resilience as operational targets, for example the achievement of flood recovery within a given time, or normative practices which maintain the privileged position of experts and the rigid application of inflexible procedures.

5.3.1 Living with natural processes: a philosophy for delivering resilience and participation

To evolve established practices of participation and resilience, and embed these ideas into future practice, it is not enough to simply argue for more participation, or more resilience (Cook et al., 2013b). Instead a more fundamental shift is necessary which re-imagines the relationship between the ecological and social systems of the catchment, or more simply the way in which people interact with every day and extreme environmental processes. Only through adopting a philosophy which actually considers these systems as an integrated whole can we move towards resilience as an adaptive or transformative force rather than the existing "*narrow, regressive, techno-rational frame centred on reactive measures*" (White and O'Hare, 2014, p. 934).

In light of the research findings presented in this thesis, I propose a new framework to bring together these currently disparate elements of participation, resilience, and catchment management. I have termed this new approach ***The Living with Natural Processes Framework*** (Figure 5-2). The framework represents a move away from the division between everyday and extreme processes and between socio- and ecological systems, which we see dominant in current management practice. Instead, it reconceptualises the way in which both socio- systems and ecological systems are managed and integrated. Participation and the unification of everyday and extreme processes is the key focus within both systems respectively, and resilience is the mechanism by which the two systems are brought together. This conceptualisation of resilience is not that of bounce-back, but instead that of evolution (Davoudi et al., 2013), embracing the changing nature of socio-ecological systems rather than attempting to separate them.

The Living with Natural Processes framework builds on three fundamental issues identified through this research, helping to address these issues and build a more sustainable and effective model of catchment management. The overall framework is new and emerges from the research undertaken for this PhD, however it is informed by and brings together existing research ideas. The three fundamental advantages are:

- Integrating people as active participants in management activities;
- unifying the management of everyday processes and extreme events; and
- embedding resilience into catchment management.

Each of these issues are discussed in turn to explain them more fully and highlight previously published research that supports this approach. The translation of the conceptual model of the Living with Natural Processes framework into a new approach to managing catchment systems will require further development and research. This is discussed further in the Recommendations section of Chapter 6.

5.3.1.1 Re-imagining people as active shareholders in environmental management

Our current approaches to participation in environmental decision-making and management position people and communities as 'outsiders' to the predominantly expert-led practices of management (Bulkely and Mol, 2003). The result of this, as shown in Chapter 2, is the dominance of participatory practices which consider participation as a mechanistic target to be achieved. These practices act to exclude people from meaningful decision-making power, with their stake in the practices of management limited to being given a voice but no meaningful power to enact change.

The Living with Natural Processes Framework seeks to reposition people and communities as active ***shareholders*** within the social system of the catchment. Re-imagining the relationship between management agencies and people in this fashion also re-imagines participation as a mechanism of governance, as argued by Challies *et al.* (2016), Evers *et al.* (2016), and Thaler and Levin-Keitel (2016); not as a target or as a tool of management, but as a philosophy or culture which guides the relationship between different stakeholders. This is similar to conceptualisation of participation incorporated in the definitions of ICM discussed in Chapter 1 (Allen et al., 2011; for example Lerner and Zheng, 2011).

Re-positioning people and communities in this fashion would enable catchment organisations such as the Greening the Twizell Partnership to exploit emerging local level aspirations for participation, such as those shown in Chapter 2. By treating these emergent participatory movements as partners, catchment organisations and management agencies could work to develop long-term trusting relationships based on shared perspectives and social learning (Benson et al., 2016; O'Donnell et al., 2018). Not only does this enhance existing expert-led practices of knowledge creation, (Chapter 3), but also offers opportunities to establish the formalised mechanisms of knowledge creation, such as citizen observatories (Starkey et al., 2017; Wehn et al., 2015), that would allow non-standard knowledge to be used more easily and effectively. As well as enhancing existing practices, Chapter 4 demonstrated the potential for new practices of knowledge creation based on participatory principles, practices which require symmetrical power relationships

(Lane et al., 2013), based on collaboration, dialogue, deliberation and negotiation (Fish et al., 2010)

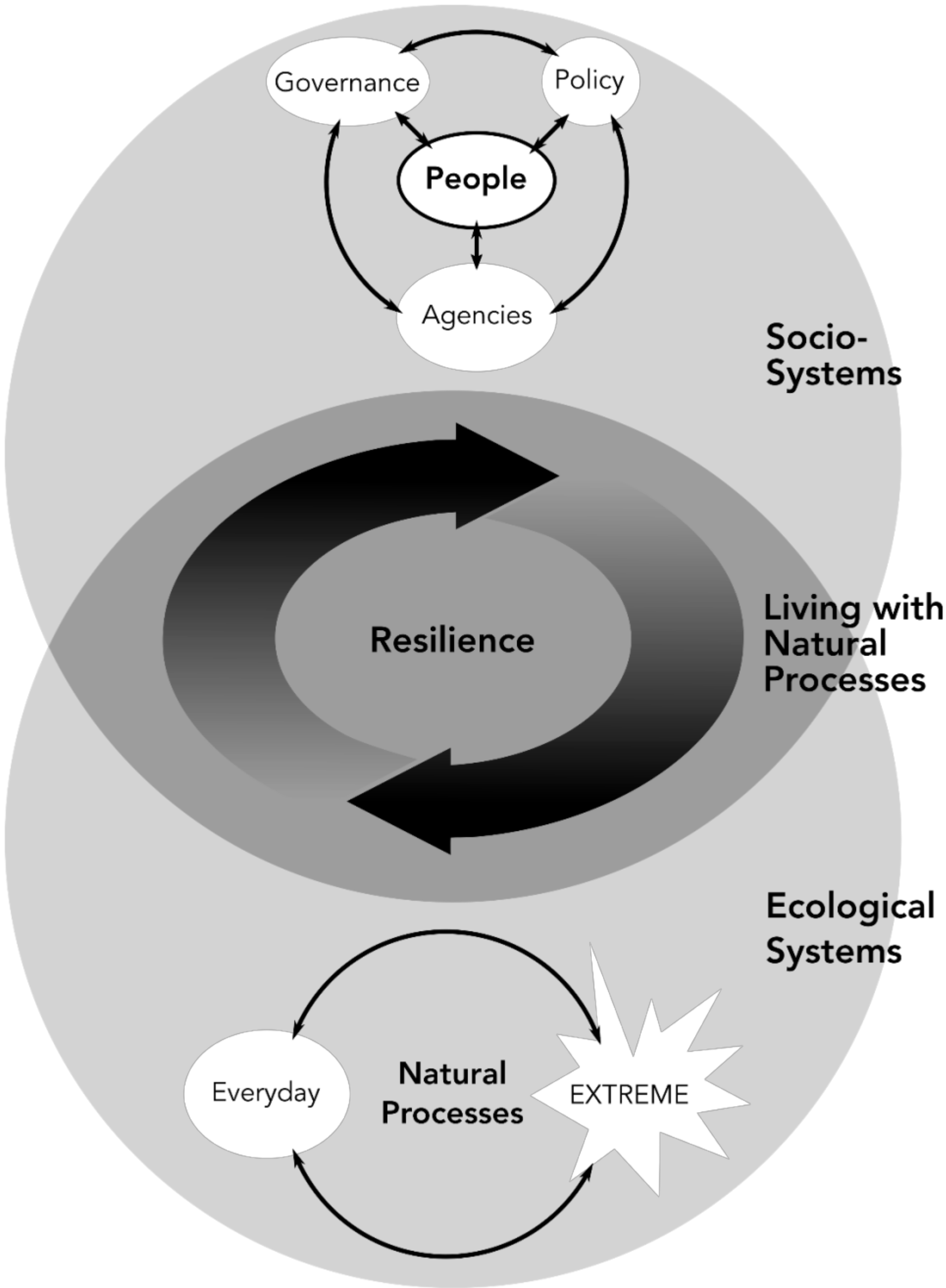


Figure 5-2. Living with Natural Processes, a new conceptual model for bringing together social and ecological systems. As a new philosophy of environmental management, Living with Natural Processes looks to unify people and natural processes through the development of resilience. Resilience is conceptualised as the overarching process through which adaptive and transformational management is achieved.

Despite the potential for enhancing our environmental management approaches, embedding a culture of participation into existing management practices would not be without significant challenges. In particular, this will require restructuring of the current top-down model of management scoping and funding which was demonstrated in Chapter 2. Participatory activities require time and flexibility to develop relationships between stakeholders, and to identify shared concerns and aspirations (Cook et al., 2013b). However, this has the potential to re-imagine local environmental problems as opportunities for local people and communities to develop their local environment and build local capacity (Chandler, 2017).

5.3.1.2 Uniting the management of everyday and extreme environmental processes

Embedding a participatory philosophy into catchment management, and treating people as active shareholders, in the management system, further undermines our present approach to the artificial division between everyday processes and extreme events. However, adopting a systems-based approach to the management of ecological systems, and not considering them as everyday processes punctuated by aberrant extreme events, has the potential to have wide ranging benefits for both participation and management activities.

Including people as shareholders in everyday management builds environmental literacy similar to, but more wide ranging than, the flood literacy proposed in Chapter 4. Similar to the flood memory concept proposed by McEwen *et al.* (2017), actively engaging people with the socio-ecological system in which they live on a day to day basis would normalise the concept of extreme events within everyday systems by embedding these events within the identity of the place in which people live; a concept proposed by Stedman (2003) and further explored by McEwen *et al.* (2014) following floods in Somerset in 2014. This 'spillover', as it has been termed by Altschuler and Corrales (2012), between knowledge of the everyday and extreme has the potential to build on community knowledge of the type shown in Chapters 2-4 and facilitate the practices of social learning necessary for the successful adoption of a participatory culture.

Unifying everyday catchment management with the management of extreme events would also facilitate the adoption of more holistic interventions. For example, the

South Stanley Sustainable Drainage project, discussed in Chapter 2, was proposed by the Greening the Twizell Partnership to target poor water quality in the Twizell Burn by reducing the load on the existing foul sewer system through the installation of sustainable drainage systems. Community-based research with local residents highlighted local flooding issues resulting from poor surface water drainage, whilst research in downstream areas of the catchment had highlighted the need to reduce or attenuate floodwater generation in the upper catchment. The local research also identified an emergent aspiration for local participation and control of the project to improve local greenspaces and provide amenity activities for young people. Despite this, the funding source chosen for the scheme was limited to providing funds only for capital works targeting freshwater quality, as a result the project was unable to exploit the potentially spatially distributed multiple benefits of delivering reduced downstream flows and local amenity value. However, considering extreme events as a part of the everyday ecological system would embed potential benefits from managing these events into everyday management.

Management of everyday ecological catchment systems and extreme events is currently heavily divided between fragmented organisations (Robins et al., 2017) with frequently competing framings of participation and how interventions should be undertaken (Collins et al., 2007). Adopting a more holistic consideration of ecological systems will therefore be challenging, particularly in tandem with the adoption of a participatory philosophy of management.

5.3.1.3 Embedding resilience

Embedding participation in catchment management and bringing together everyday and extreme event management has the effect of breaking down the current barrier between social and ecological systems. However, new practices will be necessary for socio-ecological systems to exist and be managed successfully. For example, dispersing capacity and responsibility for management to the local level is not sustainable if communities lack the ability to understand, respond to, and manage the fluctuating and uncertain nature of the ecological systems with which they co-exist.

Resilience is one mechanism through which socio-ecological systems might be governed and could co-exist. Resilience in this context does not mean the target driven, recovery-focused resilience of bounce-back that we see currently applied to FRM (Davoudi, 2012; DeVerteuil and Golubchikov, 2016). Instead, evolutionary resilience, an emergent theoretical concept proposed by Davoudi *et al.* (2013), potentially offers the mechanism by which socio-ecological systems can be combined.

In contrast to current engineering conceptualisations of resilience, the concept of evolutionary resilience expands resilience '*beyond its meaning as a buffer for conserving what you have and recovering to what you were*' (Folke et al., 2010, p. 25). Evolutionary resilience encompasses the interactions between preparedness, persistence, adaptability, and transformability at all scales (Davoudi et al., 2013). It embeds the traditional resilience concepts of preparing for and persisting against disturbances, which are key to the sustainability of social catchment systems, and the concept of living with natural processes in the here and now. In contrast to current resilience approaches, it also promotes the ability to undertake future adaptation and/or transformation in the face of diverse challenges. In the context of the living with natural processes framework, this acknowledges the intermittent nature of extreme events and the impact of slow-burning, long term changes (Davoudi et al., 2013), but also the future uncertainty represented by future changes to both ecological (Committee on Climate Change, 2016) and social systems (Kundzewicz et al., 2017; Mokrech et al., 2015). As Davoudi *et al.* (2013) argue, evolutionary resilience focuses on the "*institutionalisation of adaptability*" (p. 319) through building social learning capacity; but how might this theoretical conceptualisation be embedded within practice? Maclean *et al.* (2014) argue that developing this social learning capacity should focus on a range of issues: developing skills and knowledge; establishing robust social networks; situating people and knowledge within their specific locations and fostering local ownership; developing community infrastructure and economy; and establishing new mechanisms for more participatory governance. The living with natural processes framework offers an opportunity to practically deliver these resilience concepts by bringing together the management of socio-ecological catchment systems, incorporating participation, and uniting the everyday and the extreme.

By exploring the role of participation in ICM the research presented in this thesis has determined that, despite a widespread policy shift, practices of management remain wedded to expert-led, top-down approaches which act to exclude communities from meaningful decision-making power in the everyday management of catchment systems. In contrast, extreme flood events have demonstrated the ineffectiveness of traditional flood defence approaches and have led to a downward transfer of risk management responsibility to at-risk communities. However, communities are still not granted decision-making power, instead being expected to understand and react to top-down risk communications designed to develop 'community resilience', defined as their ability to return to a pre-event state as rapidly as possible. This disparity between everyday exclusion and extreme event participation entrenches an artificial separation between ecological and social catchment systems in which communities both live outside of everyday systems, but much cope with and become resilient to the impacts of aberrant extreme events. The unsustainable nature of this conceptualisation of catchment management has led to the proposal of a new framework, Living with Natural Processes, for combining the management of ecological and social systems into true socio-ecological systems management. The framework brings together existing research on participation in catchment management and the practices of management of everyday and extreme events in a new way, uniting these traditionally separate areas of study through the application of evolutionary resilience. By integrating people as shareholders in their environments, and considering everyday and extreme events as one, the proposed framework embeds evolutionary resilience concepts of preparedness, persistence, adaptability, and transformability into future management of socio-ecological systems.

[Page Left Intentionally Blank]

Chapter 6 Conclusions and recommendations

This thesis has presented research on the nature of public participation with integrated catchment management, exploring particularly the practices of participation demonstrated in both the management of everyday catchment processes and before extreme flood events. This is an underexplored area of study which has implications for the governance of catchment management, the role of people in environmental decision-making, the practices of everyday management and Flood Risk Management, and the development of community resilience to future environmental disturbances.

6.1 Principle conclusions from the research

The research has found that:

1. Despite a shift in overarching policy which ostensibly encourages active participation, participatory practices in everyday catchment management are limited and continue to exclude people and communities from any meaningful decision-making power at the local level. This results from a dominant vertical interplay between supra-catchment policy and funding drivers, which act to turn emergent participatory movements into obstacles to the delivery of catchment interventions. This has the effect of forcing catchment management organisations into excluding communities from participating, or allowing them to participate only through traditional, heavily structured consultation processes. This undermines emerging participatory aspirations for local ownership of environmental issues, and reinforces established expert-led practices of management and the pre-eminence of established scientific knowledge.
2. In contrast to 1., in the management of extreme flood events public participation in managing flooding at the individual level is actively encouraged, with individuals and communities expected to develop resilience to flood events. However, their role in managing floods is limited to receiving and acting on risk information provided to them by agencies operating in a traditional top-down fashion. This risk information is typically generated by experts, using numerical models which are hidden from public scrutiny. Local knowledges and experiences are not included within 'official' flood risk knowledges. Not including at-risk communities within the process of flood risk

knowledge creation has the effect of developing their appraisal of the threat without providing them with the tools to properly understand their risk or what to do about it (their coping appraisal). The adoption of engineering-based definitions of resilience as ‘bounce-back’ compound this issue, focusing on community recovery to a state of pre-event normality, rather than on long-term adaptation to flood risk.

The impact of this disparity between participatory policies and normative practices of traditional management is that the divide between social and ecological catchment systems is maintained, despite the increasing prominence of ‘integrated management’ concepts. To overcome this, the research proposes further research on how people can be more effectively integrated into existing practices of scientific knowledge creation, and also how new approaches to knowledge creation, grounded in participation and horizontal governance, can be developed. Developing these new practices will allow overarching governance structures, often grounded in traditional attitudes to the unscientific nature of local knowledges, to be challenged and re-imagined.

To this aim the research has demonstrated:

3. How local knowledge can be used to build upon established practices of knowledge creation. Using the traditionally expert-led practice of flood inundation modelling, the research showed how integrating local knowledge collected during and after a flooding event could be used to more effectively validate the processes of flooding during the event. Bringing typically competing expert and local perspectives together in this way was shown to result in more locally applicable knowledge and practices, and the research has proposed a new framework for the future validation of 2 dimensional flood inundation models.
4. The development of new, shared knowledge on flood risk and how it should be communicated using a participatory environmental competency group. By combining my expert knowledge and skills with the local, experiential knowledge of community participants, the group was able to analyse current approaches to flood risk communication and understand their limitations, before co-creating a range of proposed prototypes for new ways in which risk could be communicated. These prototypes were specifically developed to meet user information needs, developing

their threat and coping appraisals and helping them develop local resilience to future floods.

These examples have demonstrated the practical potential benefits of adopting greater participation in the integrated management of catchment systems. To apply these, the research has argued for the re-imagination of our approach to governing catchment systems, proposing a new Living with Natural Processes framework. This framework builds on the existing research base, and on the research presented in this thesis. It embeds people as active stakeholders into social management systems, and integrates the management of everyday and extreme processes within ecological systems. To bring these disconnected systems together, and to manage them as truly connected **socio-ecological** systems, the framework incorporates evolutionary resilience, a resilience approach which looks to institutionalise adaptation and evolution to both extreme and slow-burning changes. In so doing it reinforces the consideration of extreme and everyday processes, and the role of people as active stakeholders in understanding and managing temporally and spatially disparate environmental changes now and in the future.

Adopting a socio-ecological systems approach to catchment management, applied through the practices of management demonstrated by the thesis, represents an opportunity to re-imagine the way in which manage catchment systems, both everyday, and before, during, and after extreme events. Adopting the proposed Living with Natural Processes framework would overturn the current short-term, supra-catchment objective driven culture in favour of a horizontal governance model focused on the development of sustainable, locally owned catchment interventions which could adapt and evolve to meet the needs of future populations, or the challenges of future environmental changes.

6.2 Recommendations for further research

Further development of the proposals made by this research are required if a shift to an evolutionary resilience-focused, Living with Natural Processes approach is to be adopted for the management of catchment systems.

6.2.1 People as active shareholders in environmental management

Integrating people as active shareholders into existing management practices, and developing new, participatory practices, will require research to demonstrate the efficacy and benefits of adopting a wide ranging participatory approach to catchment management. This research should aim to build on the existing research base (Bracken et al., 2016; and more recently Chandler, 2017; for example Lane et al., 2011b) through upscaling and unifying the many relatively small-scale studies such as this one which has explored individual aspects of the management process. In England and Wales, Catchment Partnerships established through CaBA (Environment Agency, 2015), and less formal, emerging sub-catchment organisations such as the Greening the Twizell Partnership (Chapter 2), offer an excellent basis on which to build. Provided with the freedom and flexibility to work in a more participatory way, they would be able to undertake management more in line with the participatory ideals of their mission statements and achieve more sustainable management outcomes (Cook et al., 2013a, 2012). However, this research must also consider how emergent participatory movements and communities are identified, facilitated, and partnered with (Coates, 2015, 2010), if future management is to avoid past criticisms of participatory research as maintaining or reinforcing local power structures and excluding vulnerable or minority groups (Cooke and Kothari, 2001; Gaynor, 2014; Hickey and Mohan, 2004).

6.2.2 Developing new and practical approaches to everyday and extreme event management

Similarly, new and practical approaches will need to be explored for bringing together the management of everyday and extreme events. This should build on existing research areas, for example the move towards 'blue-green cities' (Thorne et al., 2015) and the integration of multi-purpose green spaces into urban environments, or projects targeted at upstream land management and Natural Flood Management (Waylen et al., 2017). Combining FRM activities with a participatory philosophy which considers at-risk communities as partners in management will also require significant changes to policy and practice. Our current approaches to assessing risk, determining the benefits of catchment interventions, and acceptable levels of residual risk, currently expert-led and predominantly hidden from community scrutiny (Collins et al., 2007; Lane, 2012; Thaler and Hartmann, 2016) will need to be challenged and re-assessed. To effectively achieve this, FRM agencies will need to adopt wider and more diverse perspectives on local experiences of ecological systems both everyday and during extreme events, such as those shown by this research. Research will need to demonstrate how building local capacity through embedding participation can encourage the practices of social learning (Benson et al., 2016) necessary for this to be a success.

6.2.3 Operationalising the Living with Natural Processes Framework

Bringing these two facets of the Living with Natural Processes framework together through the development of evolutionary resilience will, as discussed in Chapter 1, require overturning normative conceptualisations of resilience as preparedness and recovery which currently dominate approaches to management. Further research will therefore be necessary to demonstrate the effectiveness of the proposed framework in empowering communities and developing generalised resilience in the long term. This research will need to explore issues of **scale** (Cash et al., 2006; Maynard, 2013), and how catchment-level policy and practices can be linked with local knowledge and perspectives to generate local level interventions to build capacity and resilience (Mulligan and Rogers, 2017). This research will also need to address the long-term nature of the practices of evolutionary resilience and the impacts of both occasional extreme events and slow-burning nature of changes against which resilience is being developed. To address both of these issues in an optimal way, it will be necessary to take into account the holistic and temporal nature of the emerging socio-ecological practices of resilience developed through the framework. Doing so will require new approaches to how we can measure resilience (Lisa et al., 2015), as well as fundamental questions about what resilience ***is*** and who it is ***for*** (Cutter, 2016).

6.3 Recommendations for policy and practice

Additional research is not the only area in which work is necessarily to see the fulfilment of the Living with Natural Processes Framework. Policy, practice, and governance are also areas in which adaptation to the new framework is necessary.

There are already changes either in progress or proposed. They reflect both Britain's looming exit from the EU and the web of supra-catchment environmental legislation established at the European level (Baldock et al., 2016), and the fall-out from the winter 2014-15 floods, which saw widespread calls for a review of flood risk management governance (Environment, Food and Rural Affairs Committee, 2016). These proposed reforms have already been criticised for exaggerating the "fragmented, inefficient and ineffective" nature of English FRM, and for promoting a model of alternative governance which is at risk of damaging the integration of FRM with other environmental management through establishment of a FRM silo (Alexander et al., 2017).

Instead, a programme of change in governance, policy, and practice is necessary to implement and socialise the Living with Natural Processes Framework which focuses on increasing integration, establishing greater freedom for diverse actors, and encouraging bottom-up practices of implementation.

6.3.1 Re-invigorating environmental and flood risk management at the local scale

The proposed establishment of a National Floods Commissioner will, as argued by Alexander et al. (2017), only serve to shift FRM responsibilities up the management chain, further removing the ability of communities to have any meaningful power of management of flood risk at the local scale. Instead, the opposite approach should be taken. The Environment Agency (EA), or a similar body, should retain centralised control of FRM planning and the maintenance of technical standards and methods. However, FRM at the local scale should be distributed to reflect the local and contextual nature of flood risk at this scale. All bodies working at this local scale should be encouraged and facilitated to partner with the EA to deliver FRM (interventions, risk communication, or participatory activities) alongside their other catchment activities where integrated activities can be undertaken. This would have the multiple benefits of integrating extreme event management with the everyday management of the catchment, developing more effective and horizontally integrated partnerships at a local agency level, and also developing vertical integration by effectively bringing communities into the everyday work of agencies operating at the local level.

This act of 'place making' (Marques et al., 2018) would have the impact of helping formalise agency-community relationships, developing community capacity in self-management and participation, and facilitate the co-production of plans and interventions through the sharing of resources. These are all key factors in the more effective integration of people and communities into management of their local environments (Mattijssen et al., 2017), and the "*institutionalisation of adaptability*" (Davoudi et al., 2013, p. 319) which a cornerstone of the establishment of evolutionary resilience.

6.3.2 Re-imagining supra-catchment drivers

Policy changes, as well as changes to governance, will be necessary to deliver a meaningful shift in working practices from translating FRM responsibilities downwards. Chapter 2 demonstrated how supra-catchment drivers, stringent funding criteria, and statutory obligations for formal consultation restricted the establishment of effective participation. Fundamental change is therefore required here to support the distribution of roles recommended above. In exiting the EU, Britain has an opportunity to unpick supra-catchment drivers, such as the EU Water Framework Directive, and replace them with place-based policies (Partridge et al., 2015) which reflect the diversity of catchments and encourage a more diverse and integrated management approach. Funding also must reflect these changes in focus, with funding sources allowing much greater freedom for agencies, management bodies, and partners to undertake the integrated, often slow, and tangled task of community-focused management work. Developments in information and communications technology and smart monitoring offer opportunities to establish more effective E-governance models (Navarra and Cornford, 2005) that could overcome the risks of wastage and inefficiency in slackening control of the management process (Banerjee et al., 2016). Similarly, formal processes of public consultation, often grounded in the display of hard copy documents at public buildings, fail to reflect the modern reality of the internet and mobile phones in providing a potential portal through which engagement and participatory deliberation can be undertaken (Pereira et al., 2003). Future policy on statutory consultation must be altered to reflect this, as well as the higher levels of participation likely promoted by the changes of policy proposed above. The establishment of innovative, off- and online tools for supporting participatory activities (Afzalan et al., 2017) is essential for the collection of local information and its integration into catchment and supra-catchment datasets, as well as for facilitating the integration of people into consultation activities at all scales.

6.4 Summary

The research presented in this thesis has demonstrated that our current approaches to the 'integrated' management of catchment systems, both everyday and extreme, are fundamentally undermined by the continuing dominance of top-down approaches to management, and the adoption of metric-driven, technocratic definitions of resilience. To address this, the research has proposed new practices of people-focused knowledge creation, building on existing mechanisms of scientific knowledge creation through the use of alternative knowledges, or crafting new mechanisms of knowledge creation based on participatory governance and social learning. More fundamentally, the research has presented a new conceptual model for how participatory management of everyday and extreme processes can be unified through the adoption of a socio-ecological systems approach. This framework looks to institutionalise the concepts of evolutionary resilience which will allow management agencies and at-risk communities to work together to adapt and evolve in the face of future socio-ecological changes, whether those represent extremes or slow-burning, long-term changes.

Appendix A Publications

This appendix contains the as-published articles which constitute Chapters 2, 3 and 4 of the thesis.

[Page Left Intentionally Blank]

Journal of Environmental Management 228 (2018) 267–278

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Evaluating the success of public participation in integrated catchment management

E. Rollason[a,*], L.J. Bracken[a], R.J. Hardy[a], A.R.G. Large[b]

[a] Department of Geography, Durham University, Durham, DH1 3LE, UK
[b] School of Geography, Politics and Sociology, Newcastle University, Newcastle Upon Tyne, NE1 7RU, UK

ARTICLE INFO

Keywords:
Integrated catchment management
Catchment based approach
Governance
Participation
Framing

ABSTRACT

Recognition of the need to manage the water environment in more holistic ways has resulted in the global growth of Integrated Catchment Management (ICM). ICM is characterised by horizontal integration, encouraging interdisciplinary working between traditionally disparate management sectors, alongside vertical integration, characterised by the engagement of communities; central is the promotion of participatory governance and management decision-making. ICM has been translated into policy through, for example, the EU Water Framework Directive and at a national level by policies such as the Catchment Based Approach in England. Research exploring the implementation of these policies has reported success at a catchment level, but further research is required to explore practices of management at local level within catchments. This paper presents the findings of participatory research undertaken with a catchment partnership in the northeast of England to explore the integration of top-down policy translation with how local communities interact with management agencies at sub-catchment scale (a bottom-up perspective). The research found that supra-catchment scale drivers dominate the vertical interplay between management systems at more local levels. These drivers embed traditional practices of management, which establishes public participation as a barrier to delivery of top-down management objectives, resulting in practices that exclude communities and participatory movements at the local level. Although collaboration between agencies at the partnership scale offers a potential solution to overcoming these obstacles, the paper recommends changes to supra-catchment governance structures to encourage flexibility in developing local participatory movements as assets. Further research is necessary to develop new practices of management to integrate local people more effectively into the management process.

1. Introduction

The past two decades have seen increasing global efforts to adopt more holistic and integrated approaches to manage water environments (Watson and Howe, 2006), for example in Australia (Bellamy et al., 2002), Africa (Dungumaro and Madulu, 2003), the USA (Ballweber, 2006), and across the EU (Mouratiadou and Moran, 2007). Commonly referred to as Integrated Catchment Management (ICM) (Lerner and Zheng, 2011), these approaches use hydrological catchments as natural organising units for interventions in the landscape and natural processes (Fenemor et al., 2011). They are typified by the replacement of often fragmented and sectorally distinct approaches (Butterworth et al., 2010; Watson et al., 2009) with new, integrated land-water practices grounded in participation, shared knowledge, and social learning (Allen et al., 2011; Mitchell and Hollick, 1993; Watson and Howe, 2006).

As ICM approaches have become more widely adopted (Rouillard and Spray, 2017), studies have reported success in implementing ICM principles (Collins et al., 2007; Cook et al., 2013a). However, current research is focused predominantly on the supra-, or large catchment scale, and has typically adopted a top-down perspective (Sabatier, 1986) to assessing how effectively policy has been implemented (Watson, 2014). This has resulted in a gap in our understanding of ICM implementation at the local, or sub-catchment, scale (Mees et al., 2017), where issues have been raised about how meaningful and extensive ICM-based participation is (Mouratiadou and Moran, 2007), and whether participatory policies can overcome traditional practices of management (Cook et al., 2013b; Watson, 2014).

The purpose of this paper is to address this existing research gap by exploring the nature of integrated management practices at the local scale. In particular we look to determine how supra-catchment drivers of participation are translated into local participatory practices, and how these practices impact on communities within the catchment area.

* Corresponding author. Department of Geography, Durham University, Science Laboratories, Durham University, South Rd, Durham, DH1 3LE, UK.
E-mail address: e.d.rollason@durham.ac (E. Rollason).

https://doi.org/10.1016/j.jenvman.2018.09.024
Received 15 May 2018; Received in revised form 4 September 2018; Accepted 6 September 2018
0301-4797/

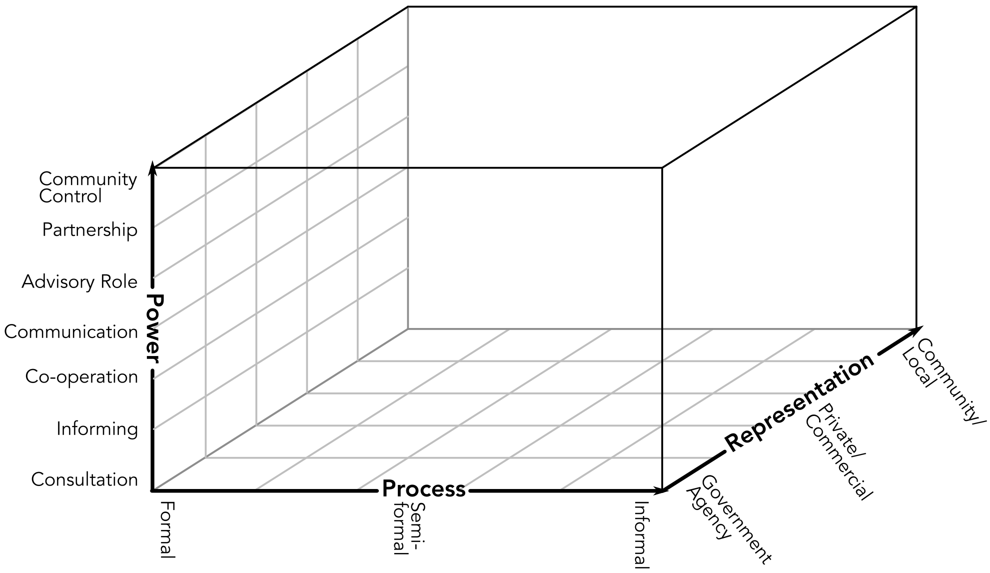


Fig. 1. Plummer and FitzGibbon's (2004) conceptual model of co-operative management. The degree of participation is assessed dependent upon and the formal or informal nature of the processes adopted (x axis), the degree to which power is transferred between groups (y axis), and which groups achieve representation (z axis) (Adapted from Plummer and FitzGibbon, 2004; and Pomeroy and Berkes, 1997).

In contrast to previous research we adopt both a 'top-down' and 'bottom-up' approach to explore the governance arrangements and working practices of a catchment management partnership, and the knowledge, experiences, and aspirations of the communities living within the area. To undertake this analysis we use the case study of a sub-catchment scale management partnership in the Northeast of England. We adopt a pragmatic, mixed methods research approach grounded in the concepts of participatory research, intended to engage with and explore a range of differing perspectives on catchment management and participation. This aims to (i) examine how the catchment partnership functions and how catchment interventions are identified, planned, and implemented; (ii) explore how community participation is conceptualised, and how it is enacted through the practices of management demonstrated by the partnership; and (iii) explore how local communities and individuals conceptualise their environment and how it should be managed, and how this interfaces with the work of the partnership.

The research presented is some of the first to consider interactions between local communities and management agencies in the day-to-day management of the environment, and how more active community participation can contribute to more effective ICM. This research is therefore crucial to determining if aspirations for community engagement are being met, and what barriers and opportunities exist for integrating people and communities into ICM practices at the local scale.

In the next section we explore ICM, and public participation in management, in more detail.

2. Background to ICM

ICM as a term is often left purposefully generic, such as the definition adopted by Lerner and Zheng (2011) as "*the fully integrated management of the land, water and human activities in* […] *catchments*" (p. 2638). This reflects the multiple objectives of ICM and the way in which it is operationalised (Butterworth et al., 2010). Taking a more detailed perspective, Kilvington et al. (2011) and Varis et al. (2014) argue that ICM represents two fundamental principles: horizontal integration, across and between management organisations from different disciplines, for example flood risk, spatial planning, or agriculture; and vertical integration between experts, policymakers, and the public. Here, we review the vertical integration component of ICM, exploring how traditional and ICM approaches to management differ in how they integrate public participation into environmental decision-making.

We acknowledge that public participation in environmental decision making is not a new phenomenon, and did not emerge specifically with a proposed shift towards ICM approaches (Reed, 2008). However, the ways in which traditional catchment management and ICM integrate people into practices of management are distinctly different (Eden, 1996). Participatory activities in traditional management are characterised by hierarchical arrangements, the dominance of expert-led decision making, and asymmetrical power relationships between management agencies and the public (Lane, 2012; Watson et al., 2009). In these circumstances participation is often heavily controlled and choreographed, and usually intended to identify public preferences for, or to 'sell', a preferred option (Warner, 2011). In contrast, ICM is characterised by a philosophy of participation aimed at dispersing and localising decision-making power (Marshall et al., 2010; Mitchell and Hollick, 1993) and combining officially sanctioned, scientific knowledge with local knowledges and perspectives (Jemberu et al., 2018; Stringer and Reed, 2007). Participation in this context is not a mechanistic target to be achieved, but an ongoing **process** which represents a fundamental part of catchment management activities (Reed, 2008).

The participatory nature of catchment management is often evaluated using conceptual models, such as Arnstein's (1969) 'Ladder of Participation'. This model classifies participation on a continuum between manipulative non-participation through to total citizen control. However, Collins and Ison (2009) argue that the model represents an over-simplified, power-focused model of participation and hence fails to consider the complex, and often non-linear, interactions between agencies and communities over time (Tritter and McCallum, 2006). In this way failure is implied if total citizen control is not obtained, even though a model of total citizen control is not always desirable or achievable (Hayward et al., 2004).

Plummer and FitzGibbon (2004), drawing on Berkes (1994) and Pomeroy and Berkes (1997), proposed a multi-dimensional model of co-operative management (Fig. 1) which extends the original power-relationships concept by exploring the interrelationships between representation, power and process. This model also considers which bodies achieve representation and the nature of participatory processes. Assessing participatory activities against power, representation and process builds on criticisms of Arnstein's original ladder, acknowledging the additional complexity of who participates and how. In this paper, we use this model to assess the degree and nature of participation in ICM.

2.1. Engagement of communities in ICM

Policy frameworks have evolved to embrace ICM and encourage public participation. The EU Water Framework Directive (WFD) focuses on both the integrated management of catchment systems (Watson and Howe, 2006) and public participation (Fritsch, 2017; Nones, 2015; Robins et al., 2017). Article 14 of the WFD requires public information supply and consultation through formal processes and encourages public participation in implementing interventions. The WFD also states that "*more* [public participation] *may be useful to reach the objective of the directive*" (Newig et al., 2014, p. 279), and so participation is expected from the general public and not just the relatively small pool of expert stakeholders typical of traditional management (Reed, 2008).

Expectations for engagement in practice can be explored by examining how the WFD is translated into policy across the EU. In England, the WFD has been translated into national policy through CaBA (Defra, 2013; Harris, 2013; Watson, 2014). This policy was intended to effectively implement the public engagement principles, linking high level policy to local level practice (Harris, 2013; Starkey and Parkin, 2015; Varis et al., 2014). CaBA envisions the management process as a series of nested and integrated practices operating at different scales. Three scales are identified, each characterised by differing approaches to participation (Fig. 2). The highest, supra-catchment, scale is the national or a river basin scale, of which there are 11 in England and Wales (Watson and Howe, 2006). CaBA work at this scale is dominated by expert-led management organisations and participatory focus is on informing and consulting (Fig. 1). The second scale is that of the individual catchment, 80 of which are defined under the WFD in England and Wales (Defra, 2013). This is the scale at which the majority of CaBA activity is focused because it has been argued that this is "*large enough to add value at a strategic scale but small enough to encourage and support local scale engagement and action*" (Defra, 2013, p. 10). Management tends to be undertaken through Catchment Partnerships (CPs) which act as collaborative fora for diverse catchment stakeholders including local authorities, management agencies, and third sector organisations representing local groups or specific issues (Harris, 2013). The third, and smallest, scale is the sub-catchment or local scale. This consists of individual locations or communities where the practices of management are applied and where individual catchment interventions are implemented. Management activities are usually undertaken by the higher level catchment partnership, however in practice in the UK and elsewhere some sub-catchment partnerships have also been formed specifically to address local issues (Environment Agency, 2015). The catchment and sub-catchment (local) scale are where participatory activities are intended to occur, including "*identifying, planning and acting* […] *with a range of stakeholders and members of the public as appropriate*" (Defra p. 6). Participation is characterised by increasing degrees of local control (Fig. 1 Advisory Role upwards), with CaBA guidance stating that participatory practices at this scale should include direct citizen involvement in both plan making and the local implementation of interventions (Defra, 2013).

ICM has therefore emerged as a mechanism for horizontal and vertical integration, embedded within EU and UK catchment management policy, and CPs have developed as collaborative fora for its implementation. However, outside of exploring horizontal and vertical integration within relatively formal structures of management there has been relatively little study of how effectively policy frameworks such as CaBA (Fig. 2) implement vertical integration and community participation on the ground (Cook et al., 2013b, 2013a, 2012). Here, we look to explore this issue, working together at the sub-catchment (local) scale both with a ICM partnership and with the communities occupying the catchment being managed. We look to examine vertical integration between the partnership and affected communities, exploring how practices of participation are enacted, and the influence of internal and external drivers.

3. Methods

3.1. Research approach

In 2015–16 research was undertaken to explore ICM practices implemented by a catchment partnership in northeast England (see Section 3.2). We explored both top-down and bottom-up perspectives using a mixed-methods approach which drew on research into participatory working with catchment groups (Bracken et al., 2016; Lane et al., 2011; Waterton et al., 2011; Whitman et al., 2015) and acknowledged the importance of exploring and understanding community-based knowledges (Bracken et al., 2015). The range of methods was invaluable in gaining community trust, identifying research participants, and obtaining a wider understanding of community concerns and aspirations.

3.1.1. Data collection

Our focus was on recording and understanding the work of the catchment partnership and its relevant partners (see Supplementary Information), but also local knowledge, attitudes and aspirations of the communities within the area (Section 3). To do this we adopted a pragmatic, mixed-methods approach to collect as wide a range of data as possible (Table 1).

Participatory mapping (McCall, 2008) and walking interviews (Evans and Jones, 2011) were used to explore individual's local knowledge and experiences within the context of their local environment.

Participatory mapping has been shown to be a valuable tool in assessing local needs and analysing local problems, perceptions, and priorities (Dekens, 2007). Participatory mapping was conducted on an individual basis, in the form of unstructured interviews, and through open workshops and drop-in sessions at existing community events. The majority of participants in these sessions were male, aged between 44 and 65, and retired, although they came from a variety of professional backgrounds. This reflects both the composition of the communities within which the research took place and also the availability of participants during the research period.

Discussions were participant-driven, using the theme of 'what do you know about the environment of the Twizell Burn?' as a broad introductory framework, and with a hard-copy map of the local area to provide context and an aid to discussions. Participants were encouraged to discuss their knowledge and opinions, using the map as a prompt, with locations or extents hand drawn on the maps and annotated. Additions to the maps were digitised and integrated with transcribed discussions to produce a qualitative GIS as proposed by Cope and Elwood (2009). Interview discussions were audio recorded, although discussions at drop-ins and community workshops were not, with the interviewer indicating locations on the map to which the discussions could be linked during analysis. The locationality of knowledge, the relationship between the knowledge being collected and the locations being referred to within the catchment, was the principle focus of the interviews and other discussions and recording this effectively was therefore essential. Formal recording or analysis of participants speech, for example voice tone or emotions, was not carried out as this analysis would not have been applicable to the wider dataset due to the diverse nature of the interactions, with some being recorded and transcribed and others not.

Participatory mapping was supplemented by 'walking interviews'. These enabled explorations of how knowledge and experience was situated or concentrated within different parts of the catchment through physically placing participants within their environment (Jones et al., 2008). Walking interviews were also unstructured, with the routes of walks determined by the interviewee, natural go-alongs (Kusenbach, 2003) or participatory walking interviews (Clark and Emmel, 2008) using the typology developed by Evans and Jones (2011). Walking interviews were undertaken on a one-to-on basis. Interviews were GPS-

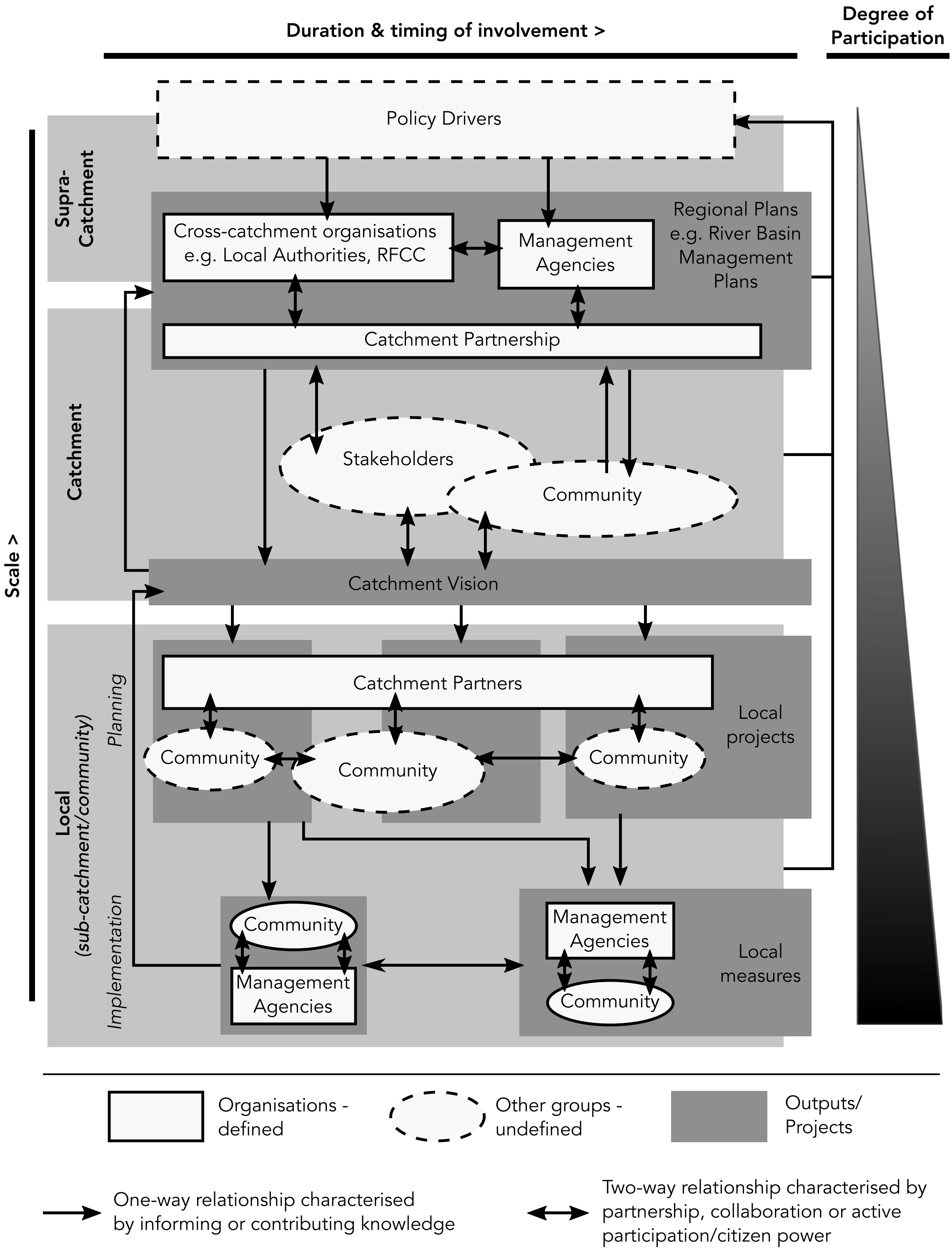


Fig. 2. A conceptual model showing the principle drivers, outputs, organisations, and the participatory nature of their relationships which underpin Integrated Catchment Management as conceived through the UK Catchment Based Approach. The x axis indicates the broad duration and timing of different relationships, whilst the y axis indicates catchment scale.

tracked and audio-recorded to allow subsequent locational analysis of participant's knowledge during data analysis, as demonstrated by Jones and Evans (2012). Employing these methods allowed discussions to be free and participant-focused and uninterrupted by note taking.

Where possible we also undertook less structured ethnography. This included using local community spaces such as community centres to informally discuss the research activities with local residents, staff and patrons. We also participated in meetings of the catchment partnership, engaged in the planning and development of several catchment interventions and participated in a regular walking group. In this way our research was grounded in the principles of ethnography and participant observation, qualitative methodologies based on the observation and participation of researchers in the activities being studied (Atkinson and Hammersley, 1994). These methods enabled researchers to explore

Table 1
The research methods adopted during the study and the data collected. Data was collected predominantly between spring 2015 and summer 2016 during fieldwork in the Twizell Burn Catchment and with the Greening the Twizell Partnership (see Section 3.2).

Data Type		Source	Quantity/Data
Participatory Mapping		Interview transcripts and annotated mapping (transferred to GIS data by researchers) from one-to-one participatory mapping interviews.	4
		Annotated mapping and text comments ((transferred to GIS data by researchers) from participants at three drop-in sessions held in support of partnership activities	Three drop-in sessions held at local community centre to support partnership activities.
Walking Interviews		Interview transcripts and GPS trace of route from walking interviews. Supported by post-interview notes taken by researcher.	2
Community Ethnography	Ongoing community participation between December 2015 and March 2016, including attending community cafes, and participation in community walking groups.	Ongoing note-taking from researchers about their interactions with community members.	
Ethnography	Participation in Catchment Partnership activities between May 2015 and September 2016. In particular attendance at Steering Group meetings and involvement in the planning and/or implementation management projects.	Ongoing note taking from researchers Notes from meetings Reports and documentation from management agencies	

participants' points of view and what their actions or behaviours meant within the context of their environment (Gobo, 2011).

No formal data recording took place during the ethnographic research. Instead, the researchers maintained detailed field notebooks of interactions that focused on who had participated in discussions, the main interactions between different individuals and organisations, and how decisions were made. Notes were supported by examination of official meeting minutes and documents arising from the work of the catchment partnership.

3.1.2. Data analysis

The empirical data collected during the study (Section 4) represented an unstructured and highly diverse, 'format messy' dataset consisting of locational data, transcripts of interviews, participatory mapping, and official documents. The nature of the dataset, whereby data on particular locations or regarding particular issues might be drawn from multiple sources and/or data formats made the adoption of a single, formal method of analysis difficult. To analyse these data we therefore adopted a pragmatic, grounded theory and grounded visualisation approach following Charmaz (2011) and Knigge and Cope (2006). This approach looks to integrate diverse empirical material in a flexible, and reflexive, way both during and after the data collection. The focus of the analysis was on identifying key knowledge and themes to explore the practices of management demonstrated and experienced by local communities.

3.2. The study area: the Twizell Burn catchment

The research was undertaken in the Twizell Burn, a tributary of the River Wear located in northeast England, UK (Fig. 3), an area managed by the Wear Catchment Partnership; a catchment organisation established officially under the CaBA. The catchment is mixed urban-rural and is heavily influenced by historic mining activity, both deep pits and more recent opencast. The water environment reflects its history: it is classified under the WFD as heavily modified and achieves only moderate ecological status (Environment Agency, 2018) as a result of sewage outflows, agricultural pollution, and the dewatering of historic mine workings (Groundworks NE and Cumbria, 2015). There is a history of management intervention in the upper catchment to remediate the effects of historic mining activity (Jarvis and Younger, 1999).

4. Results

In this section we initially adopt a top-down perspective to present the governance structures which shape management within the catchment, and the practices of management shown by the agencies working through a local partnership. Secondly, we adopt a bottom-up perspective, to present the viewpoint of the local community, focusing particularly on local knowledge and engagement with the catchment of the Twizell Burn, and the interactions of local participants with the activities of the partnership.

4.1. Catchment governance: establishing the Greening the Twizell Partnership

In 2015 Durham County Council (DCC), the local spatial planning authority, commissioned Groundworks NE & Cumbria (Groundworks), a local third sector organisation, to prepare a Green Infrastructure Masterplan for the Twizell Burn. The aim of this plan was to develop an integrated strategy for how the catchment should be managed by the diverse range of agencies with management duties or interests in the area (Groundworks NE and Cumbria, 2015). This work was founded on a period of public consultation, undertaken by Groundworks between October and December 2015. This consultation included four public meetings and an online questionnaire survey undertaken with communities across the catchment and in urban areas immediately adjacent; approximately 100 people were engaged by this process (Groundworks NE and Cumbria, 2015). Four workshops were also held between professional and community organisations within the area. Information derived from the exercise was used to develop the Green Infrastructure Masterplan, which identified a wide range of potential opportunities for integrated management of the Twizell Burn catchment (Groundworks NE and Cumbria, 2015). A key proposal was to establish a sub-catchment based partnership, the 'Greening the Twizell Partnership' (GtTP), charged with delivering the proposed management interventions. The aspiration of the partnership reflected both the ethos of collaborative management laid out in the CaBA, but also the participatory philosophy of wider ICM concepts:

> *"The purpose of the Partnership is to be **representative of stakeholders and the community** who are interested in making a difference in the Twizell catchment area [and to] **work together** to […] meet the vision and objectives for the Twizell burn" (Groundworks NE and Cumbria, 2015, p. 126 - emphasis added).*

The GtTP was established in 2015 and was initially chaired by the Wear Rivers Trust (WRT), a local third sector environmental organisation and chair of the River Wear Catchment Partnership, the CaBA partnership at the spatial scale above that of the study area. Other partners included the Environment Agency (EA) and Northumbrian Water Group (NWG), Durham County Council (DCC) and Stanley local

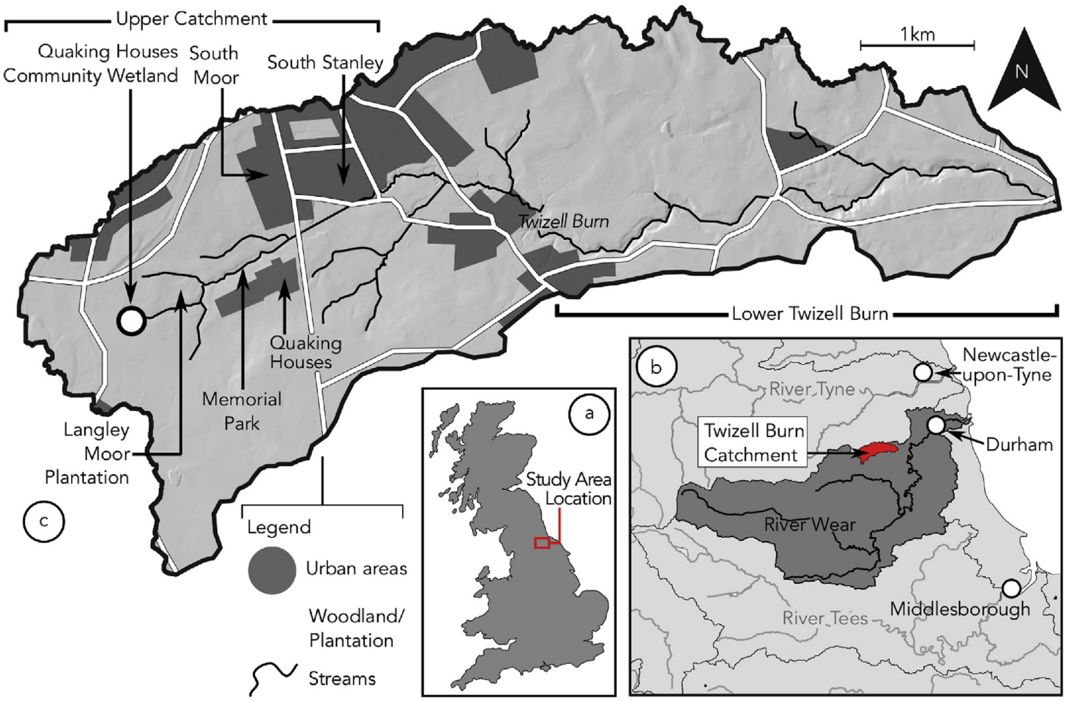


Fig. 3. (a) The location of the study area within (b) the catchment of the River Wear, and an overview of the Twizell Burn catchment showing the location of places referred to in the text.

town council. The partnership was supported by an engineering firm, Fairhurst Environmental, contracted by DCC, and Groundworks. Public representation was through the attendance of two elected local councillors, one of whom took over as chair of the GtTP steering group in 2017. Further information on partner organisations can be found in the Supplementary Information to this paper.

The GtTP's aim, outlined in the partnership agreement was:

"to improve environmental sustainability in the area surrounding the River Twizell through community engagement, and collaborative working between relevant organisations and institutions." (GtTP, Personal Communication)

4.2. Catchment management practices: who participated and how?

Six principal interventions were planned and/or implemented by the GtTP during the research period (for details see Supplementary Information). Of these, two were 'bundles' of interventions comprising smaller interventions connected either by location, in the case of the South Moor Regeneration Works, or by focus, in the case of the Upper Catchment Works.

The interventions were predominantly carried out by two bodies: WRT undertook works focused principally on water quality and biodiversity in the lower parts of Twizell Burn (Fish Passage Works and Habitat Improvements) and distributed across tributaries in the upper catchment (Upper Catchment Works). Works by DCC, working together with Fairhurst Environmental, centred on the area of South Moor. These works concentrated on the general rehabilitation of the urban area including housing regeneration, the retrofitting of Sustainable Drainage Systems (SuDS), with multiple benefits including greening a high density urban area with improvement of downstream water quality and the installation of a heritage trail to illustrate the area's World War 1 heritage.

The practices of participation were distinct between the two agencies. Some limited consultation was undertaken by the WRT with the local angling club to identify locations within the lower Twizell Burn where habitat improvements and the installation of fish passes were necessary. This was informal and based on private contacts between WRT and the angling club; there was no public involvement in the detailed planning and implementation of these measures. In the upper catchment there was no participation in the planning of interventions which were based on scientific data and expert knowledge alone. Once these works were designed and funding had been obtained, volunteers were used to facilitate implementation. Volunteers had no role in decision-making and no long-term engagement was planned or carried out. Interventions were intended to be low maintenance and require little or no future intervention.

For the South Stanley Sustainable Drainage intervention our participatory community based research, which included concerns and aspirations for the proposed works (Section 4.3), could not be used to inform the project due to strict project scoping requirements set by the funder (see Section 5). As a result the proposal was based entirely on scientific data and expert knowledge.

In contrast, the South Moor Regeneration works included extended, formal consultation processes in their planning phases. Local residents had opportunities to comment on proposals, with views used to inform development of the final design. Consultation continued during implementation of these works and local residents developed a semi-formal co-operative arrangement with DCC staff to help facilitate interventions. This relationship has been sustained and continues to function at South Moor.

Only the development of the South Moor Heritage Trail saw deeper, less formal participation, bordering on local control. The planning and implementation of the trail was informed by a partnership between DCC and local community groups (for example walking and history groups) which collected archival data on the local area and determined the route for the circular walk. Ongoing engagement includes a community-controlled website and blog to document the development of the route and its use.

4.3. Opportunities for local knowledge, engagement, and participation in the Twizell Burn catchment

Results showed particular engagement with issues of flooding and

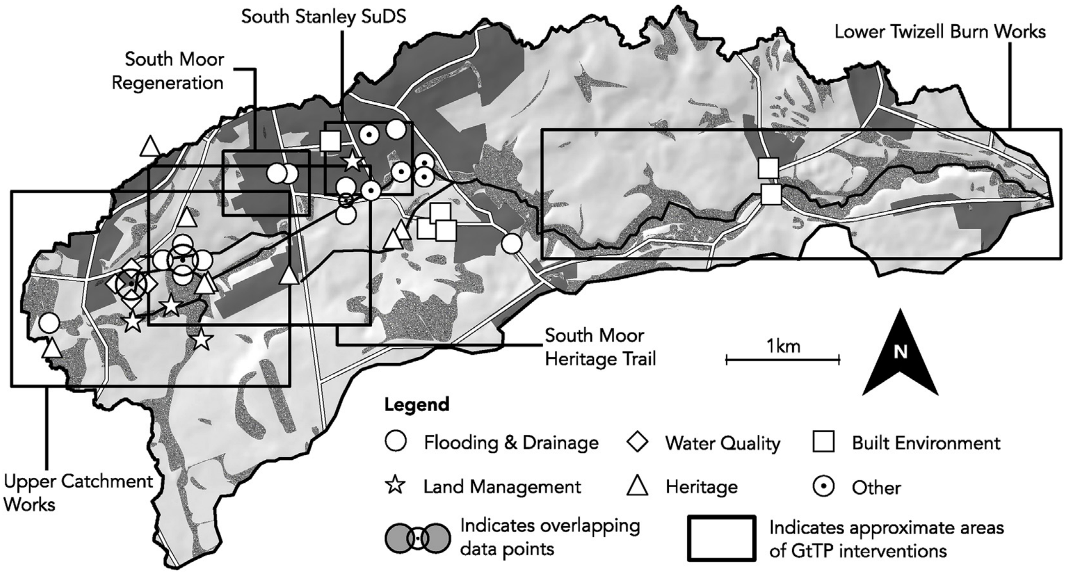


Fig. 4. Distribution and classification of local knowledge about the Twizell Burn and its catchment collected during the participatory research. Data is displayed in point format even though some data represents knowledge distributed across an area. Boxes show the spatial relationship between local knowledge collected during the participatory research and the GtTP interventions discussed in Section 3.2.

drainage across the catchment, as well as land management and the amenity value of the local environment (Fig. 4). These latter issues were often conflated as participants were predominantly interested in land management to allow greater access to the burn, for example the establishment of rights of way and access gates.

Knowledge of flooding and drainage emerged from routine local problems, such as blocked drains or highway runoff, but also included recent fluvial flood events. Participants were keen to discuss flood management, for example highlighting increases in localised surface water flooding related to new housing developments and resulting increased areas of impermeable surface. Several participants showed detailed understandings of the impact of historical development on the hydrology of the catchment, providing information on the course of historically culverted watercourses and identifying inaccuracies in GtTP mapping of the catchment extent.

Only a minority of participants highlighted issues of water quality or the creation of habitats. Such information predominantly related to areas of the upper catchment historically affected by minewater run-off (although this was not seen as a current problem), or sewage discharged from Combined Sewer Overflows (CSOs). These issues were noted because of their impact on the amenity value of the stream, rather than on water quality itself.

4.3.1. *Engagement with Greening the Twizell Partnership activities*

Participants reported little or no engagement with the initial consultation workshops undertaken by Groundworks for the Green Infrastructure Masterplan; although some felt they had been actively excluded. One participant expressed anger because he had attempted to contribute local knowledge of the catchment extent and drainage pathways, derived from his local knowledge, during the workshop. He felt that his knowledge had been rejected by facilitators because his information, based on an 'on the ground' knowledge of the local hydrology, conflicted with the official maps derived from national scale mapping. He felt his knowledge was dismissed because it was not 'official' and therefore could not be correct.

Almost all participants felt that no information on the GtTP, its vision for the catchment, or details of any of the proposed interventions had been communicated to them. Some participants had received information in an ad-hoc fashion through personal contacts with agency staff, but this was often fragmentary or out of date. Some participants in the upper catchment contrasted the lack of engagement with the GtTP with the historic construction of the Quaking Houses Community Wetland (Fig. 3), a collaborative project between the Quaking Houses Environmental Trust (a disbanded local environmental group), and Newcastle University. The wetland had been constructed to treat contaminated minewater; a locally identified environmental issue (Jarvis and Younger, 1999). Whereas the Quaking Houses Wetland had been a community-led research project (Kemp and Griffiths, 1999), the lack of contact from the GtTP, particularly as some of the proposed interventions involved replacing the now derelict Quaking Houses Wetland, made them feel actively excluded from the works being undertaken.

The longer-term outcomes of the interventions were also a source of concern. Previous one-off agency interventions were dubbed 'helicopter projects', where management agencies landed to undertake capital works before taking off again. These interventions resulted in only short-term gains, unsupported by ongoing community activity. These previous projects were contrasted unfavourably with the GtTP interventions, particularly as no information was provided by the GtTP about their low-maintenance designs or their intended lifespan. As well as having limited local benefits, these interventions were perceived to exclude local people. This was because time invested by individuals was essentially wasted once the management organisations moved on. These feelings were compounded by the fact that none of the participants felt that local communities were able to take longer-term ownership of interventions.

5. Discussion

The results indicate that the practices of management and participation demonstrated by the GtTP were dominated by top-down, hierarchical approaches and practices typical of traditional catchment management. These findings support research by Cook (2013b) which highlighted how practices of traditional management persist due to the embedded nature of traditionally grounded policies and practices which shape emergent catchment organisations such as the GtTP.

The dominance of traditional, top-down approaches is demonstrated by the establishment of the governance arrangements for the catchment. The translation of "*The purpose of the Partnership is to be representative of stakeholders and the community* [… and to] ***work together*** *to* […] *meet the vision and objectives for the Twizell burn*" (Groundworks NE and Cumbria, 2015, p. 126) into an aim of undertaking management "*through community engagement*" (GtTP, Personal

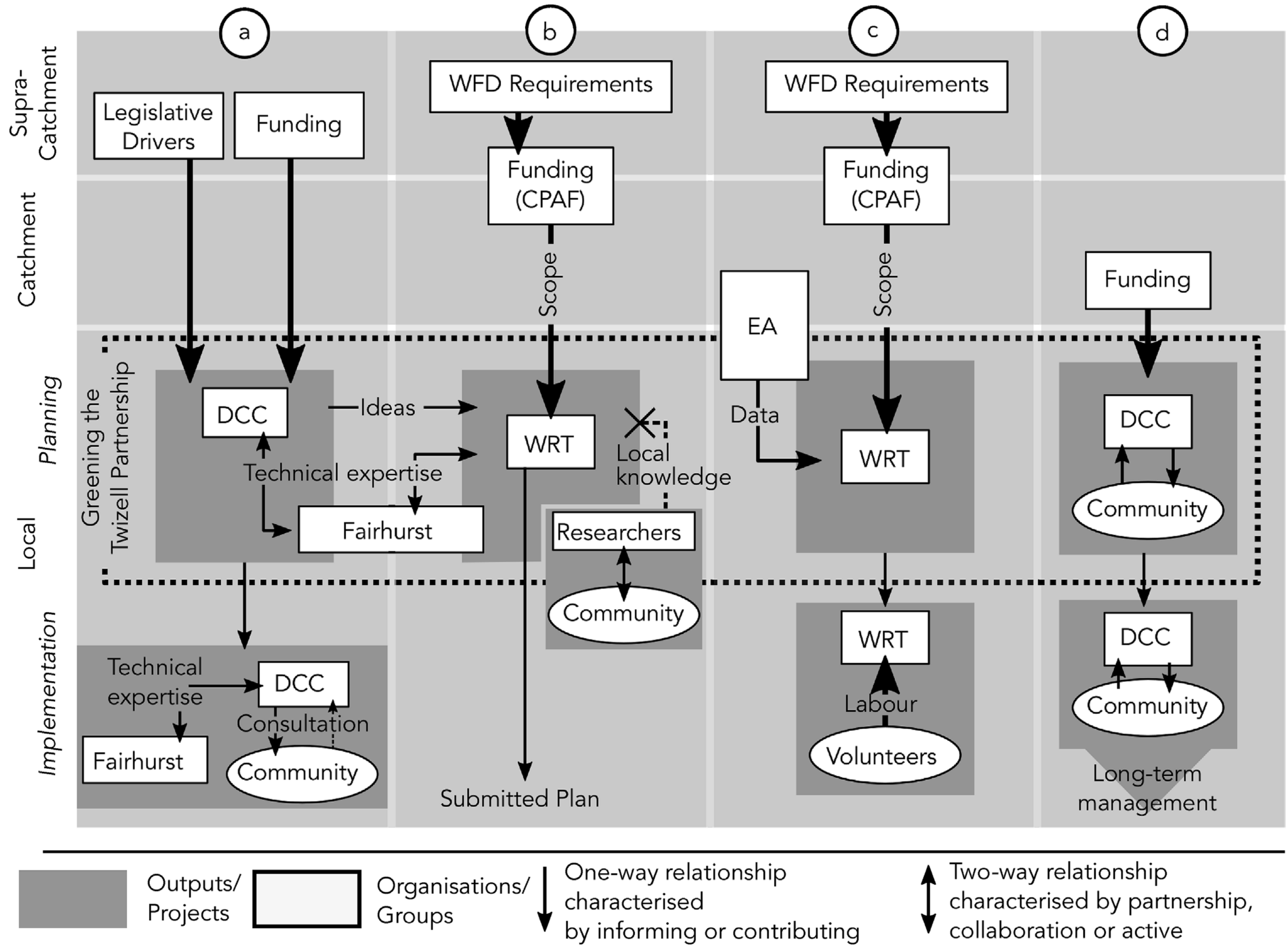


Fig. 5. Characterising the nature of public participation in the planning, implementation, and outcomes of catchment interventions carried out by the GtTP using Plummer and FitzGibbon's (2004) conceptual model of co-operative management. Interventions mapped are (1, 3, 4) Upper Catchment Works, (6, 7) South Moor Regeneration Works, (8) South Stanley Sustainable Drainage Project, (9) South Moor Heritage Trail, (10) Fish Passage Works, and (11) Habitat Improvements. Further details of these interventions can be found in the Supplementary Information to this paper.

Communication) represents a significant shift from a participation-focused philosophy to one much more reminiscent of traditional management. Additionally, although "community engagement" was identified as a principle aspect of the GtTP's aim, the way in which the working practices of the partnership were operationalised acted to close down planned participatory activities. The role of local communities was limited to that of providers of information, with activities dominated by 'expert-led' practices (Fischer, 2000), and the practices of the GtTP to traditional consultation (Greening the Twizell Partnership, Personal Communication). Informing and consulting represent a low degree of power transfer in the decision making process (Fig. 1), and formal processes are typical of traditional management (Warner, 2006).

The dominance of traditional management approaches is also demonstrated by the practices of participation evident in the interventions planned and implemented by the GtTP. Fig. 5 maps the nature of participation demonstrated onto Plummer and FitzGibbon's (2004) multi-dimensional model of participation (Fig. 1), and shows that interventions have a very limited local control (Plummer and FitzGibbon, 2004) at almost all stages of the planning, implementation and outcomes of each intervention. For example in the Upper Catchment Works (Fig. 5 Nos 1, 3, and 4), participation is limited to the implementation phase with the informal use of volunteers. In contrast, the South Stanley SuDS intervention carried out by Durham County Council (Fig. 5 No 7) was characterised by formal processes of consultation at all stages, intended to inform expert-led decision-making. Only one project, the South Moor Heritage Trail (Fig. 5 No 9), demonstrated participatory practices and local control of both the planning and implementation stages, as well as potentially longer term participatory outcomes. This analysis also shows the advantages of using a multi-dimensional model of participation over Arnstein's (1969) relatively simplistic ladder of participation, as the original ladder would be unable to differentiate between these two practices of management, focusing instead predominantly on the outcomes which are largely the same in both cases.

5.1. Vertical integration in the practices of management of the GtTP

The driving top-down policy, CaBA, uses the sub-catchment as the key scale for the implementation of community-led, participatory activities. However research findings from our community-focused research and activities to develop the Green Infrastructure Masterplan demonstrate that these aspirations are not delivered. This bottom-up research indicated a broad understanding and engagement with the catchment of the Twizell Burn from local communities. An emergent aspiration for participation and local control related to a range of issues which extended widely beyond the relatively narrow focus of the GtTP was also evident.

We explain this apparent disjuncture between policy, emergent aspirations for participation, and the practices of participation

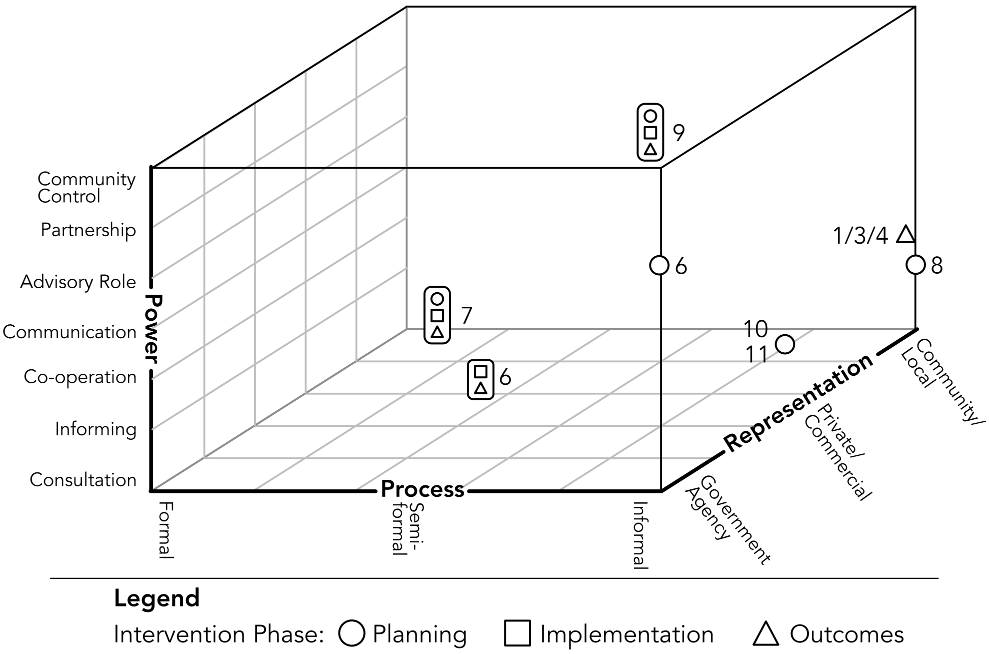


Fig. 6. Mapping the vertical interplay between drivers and actors at different scales within the management process in the Twizell Burn. Interventions mapped are (a) South Moor Regeneration Works, (b) South Stanley Sustainable Drainage Project, (c) Upper Catchment Works, and (d) South Moor Heritage Trail. The actors referred to within the figure represent the main agencies within the GtTP discussed in Section 3.

demonstrated by the GtTP by exploring the vertical interplay between the drivers of management and participation occurring at different scales within the management process (Watson, 2014; Young, 2006). Young (2006) argues that vertical interplays are interactions between management systems occurring at different scales; in this case the local, catchment, and supra-catchment scales (Fig. 2). These management systems have different policy instruments, systems, and associated behaviours (Watson, 2014). Contrasting systems at different scales can result in differing outcomes depending upon the relationship between the scales. Young (2006) proposed five potential modes of interaction characterised by their degree of integration, ranging from the dominance of a higher level system through to the integration of two systems resulting in systemic change.

Fig. 6 maps four of the interventions undertaken by the GtTP against Young's conceptual model, exploring drivers and principle actors at each scale to illustrate the vertical interplays in each case. Interventions (a-c) represent the majority of the interventions carried out by the GtTP, whilst (d) shows the South Moor Heritage Trail; the only intervention to achieve meaningful local participation. Results indicate that the routine practices of the GtTP are characterised by a dominant vertical interplay (Young, 2006), with participation at the local level dominated by supra-catchment drivers. Two principal sources of drivers are apparent depending on the focus of interventions. For WRT-led projects (Fig. 6a and b), the WFD acts as the driver, establishing top-down objectives for the achievement of minimum water quality standards for the Twizell Burn (Voulvoulis et al., 2017). These supra-catchment objectives are translated to the local level through the provision of project funding, provided in this case by the Catchment Partnership Action Fund (CPAF) (Defra, 2016). This funding is heavily controlled and provided only to projects targeted at WFD compliance. It provides funds for immediate capital expenditure and not for ongoing maintenance or engagement work. Use of this funding source forced WRT to maintain tight control of the planning and implementation of these interventions (Cook et al., 2013b; Mees et al., 2017) since the inclusion of unfocused local aspirations represented a significant barrier to obtaining the funding. Hence WRT was unable to use the data collected during the South Stanley SuDs project as, although the data highlighted the potential for a wide-ranging, locally controlled project with multiple benefits, this was not achievable through CPAF funding. Instead, WRT was forced to adopt a model of participation that, following Plummer and FitzGibbon's (2004) model (Fig. 5 No 8), undertook engagement as an informal process with very limited representation, with only those who could contribute relevant knowledge, skills, or labour asked to participate, and no transfer of decision-making power. The lack of long-term involvement by WRT in these interventions, dictated by the use of CPAF funding, meant that there was no potential for these limited participatory practices to develop into anything further (Schild, 2018).

For DCC-led urban regeneration projects (Fig. 6a), supra-catchment legislation, including the Planning Act 2008 and Localism Act 2011, dictates how the council, as spatial planning authority, must function (Landmark Chambers, 2014; Ministry of Housing, Communities & Local Government, 2017). This legislation is grounded in traditional approaches to consultation, with mandated formal practices to demonstrate due process in the event of planning disputes (Blowers, 2017). Evidence of these approaches are seen in the formal practices adopted during the South Moor Regeneration Works, with only a low transfer of power through formal processes, although representation is widespread within the local area (Plummer and FitzGibbon, 2004). Participation is once again a barrier to achieving interventions, albeit different to that experienced by WRT. Delivery of statutory duties means DCC practices are not aligned with deeper community participation, resulting in a practical barrier in terms of limited time and resources (Cook et al., 2012). The subsequent development of a semi-formal, co-operative relationship between DCC staff and local residents demonstrates the benefits of participation and the willingness of DCC staff to adopt a more flexible approach to participation when it is clearly beneficial to their interventions.

The only project with a deeper participation and local control was the South Moor Heritage Trail since the vertical interplay is not dominated by supra-catchment drivers with top-down objectives (Fig. 6d). Local participation here was not a barrier, but a driver. The project was therefore able to develop a participatory model closer to the collaborative ideals of ICM (Marshall et al., 2010), with high levels of local representation through an informal and ongoing process and the dispersion of decision-making power to local groups; both in the planning and long-term management of the intervention.

5.2. Horizontal integration in management practices

Whilst the results indicate limited success in achieving vertical integration, they demonstrate the emergence of a successful form of collaborative, horizontally integrated management between members of the GtTP (Varis et al., 2014). Projects, regardless of their supra-catchment drivers were all funnelled through the GtTP (Fig. 6) which enabled the group to act as a collaborative forum in which a degree of social learning (Allen et al., 2011; Collins and Ison, 2009), along with development of shared goals could be achieved between representatives of traditionally discrete agencies. This is evidenced through the development of the original Green Infrastructure Masterplan, which envisioned a systems-based approach to the management of the Twizell Burn and the development of a range of interventions targeting ecological and socio-ecological systems. Collaboration between different agencies in the sharing of ideas, expertise and data occurred (Margerum, 1999), for example the use of DCC project data arising from the South Moor Surface Water Management Plan used to inform the South Stanley SuDS project (Fig. 6a and b). However, this collaboration was limited and based mainly on personal relationships developed between specific individuals within the GtTP, including long-standing professional relationships. One aspect where collaboration was unable to achieve more effective systems working and better vertical integration, is in breaking out of the path dependency (Kirk et al., 2007) dictated to each agency by its supra-catchment drivers. This reflects the fact that social learning was undertaken on an individual level between specific members of the GtTP, and was not representative of wider institutional processes of social learning. More 'official' processes, or deeper relationships between individuals from professional organisations would be necessary for the agencies represented within the GtTP to break out of their traditional management paths. However, the development of these collaborative forms of working offers hope that further development of these relationships might facilitate more diverse working practices. Agencies would also be able to call on a wider suite of funding sources (Cook et al., 2013b), thereby reducing the dominant vertical interplay evidenced by this research. Reducing the dominance of supra-catchment drivers on local practices would remove the barrier of participation demonstrated here. The emergence of bottom-up aspirations for participation would be an asset to planning, delivering, and maintaining locally relevant and integrated management interventions.

6. Conclusions and recommendations

Catchment management has been ostensibly revolutionised by the participatory principles of ICM. Policies mandating citizen participation in planning and decision-making are now widespread, for example the Water Framework Directive, with the management system conceptualised by nested cycles of partnership working (Fig. 2). However, nearly twenty years after the WFD was implemented across the EU widespread research has shown that catchment management at the local, sub-catchment scale remains dominated by traditional, top-down approaches which exclude local communities from any meaningful participation in catchment management. These practices result from a dominant vertical interplay between supra-catchment drivers and local practices which restricts vertical integration between agencies and communities within the catchment. Participation is limited in either power transfer and/or representation (Fig. 5) by the tightly controlled scope of catchment interventions, designed to meet strict funding criteria set at the supra-catchment level, or by the processes used by statutory bodies for formal consultation, again dictated from the supra-catchment level.

Hence despite a policy aspiration for integrating bottom-up participation into catchment management, emergent participatory movements, such as that shown in the Twizell Burn, which are characterised by multiple and complex knowledges and aspirations for management activities, remain obstacles to achieving supra-catchment objectives. Only where these supra-catchment drivers were absent did deeper participatory practices emerge.

The results presented here show the emergence of a greater degree of horizontal integration between agencies, allowing traditionally distinct sectors of management activity to be brought together. By working more closely together, opportunities to exploit or share new funding sources outside of their traditional domains may be opened up, potentially enabling time and flexibility for greater vertical integration to emerge. Although this is positive, catchment groups in other areas must navigate different vertical interplays depending on their local circumstances, and therefore emergent horizontal integration cannot be relied upon to drive vertical integration and the meaningful integration of communities into environmental decision-making.

Instead of acting as a barrier to implementing management, local knowledge and participatory aspirations should be an opportunity to develop effective and locally driven management practices. Further work is necessary to move participatory activities away from the low-power-low-representation or low-power-formal-process models demonstrated in this research, in particular:

1. The supra-catchment governance structures which currently control catchment management at the local scale must be challenged and restructured. Meaningful participation within ICM requires time, to establish informal, trusting relationships with local communities, and flexibility of process, to work together with emerging participatory movements. Future practice and research in ICM should explore how local-level governance structures can be established, to diversify practices of management, reduce the influence of the supra-catchment drivers, and revive meaningful localism.
2. The ways in which participatory governance of local environmental issues might be undertaken should be examined to demonstrate how management organisations can enhance their work through meaningful vertical integration. The policies and practices of traditional governance exclude local knowledges as 'unscientific' and incompatible with the scientific, expert-driven management practices (Eden, 1996). However, research has long challenged this view (Wynne, 1996).
3. To support the establishment of more participatory catchment governance structures, research should demonstrate: (i) how the credibility of different information sources can be assessed; (ii) how alternative knowledges can be used within existing frameworks of knowledge creation to inform decision-making; and (iii) how new mechanisms for social learning and shared decision-making can be established to implement the renewed localism needed in ICM practice.

Supra-catchment policies such as the WFD have fundamentally altered how catchments are managed, attempting to encourage the bottom-up management of catchments through participatory practices. However, this research has demonstrated, nearly twenty years after the WFD came into force, the difficulties of changing embedded practices of management dictated by a complex and interlocking array of drivers operating on different actors and at different scales within the management cycle. Only by addressing both policy and governance at the supra-catchment level, to encourage flexibility and self-determination at the local level, and developing tools and practices, to bring together alternative knowledges and perspectives, can this disparity be overcome and the participatory culture of ICM be embedded within catchment management practice.

Funding

This work was supported by the Natural Environment Research Council [grant number NE/L002590/1].

Data

Data presented in this manuscript can be obtained by contacting ER.

Acknowledgements

The authors would like to thank the members of the Greening the Twizell Partnership, as well as the individuals and communities from the Twizell Burn catchment, for their participation in this study. We would also like to thank Prof Glenn McGregor and Dr Nigel Watson for their comments during the development of this paper, as well the work of the editors and reviewers whose comments have helped to strengthen the final manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.09.024.

References

Allen, W., Fenemor, A., Kilvington, M., Harmsworth, G., Young, R., Deans, N., Horn, C., Phillips, C., Montes de Oca, O., Ataria, J., Smith, R., 2011. Building collaboration and learning in integrated catchment management: the importance of social process and multiple engagement approaches. N. Z. J. Mar. Freshw. Res. 45, 525–539. https://doi.org/10.1080/00288330.2011.592197.

Arnstein, S.R., 1969. A ladder of citizen participation. J. Am. Inst. Plan. 35, 216–224. https://doi.org/10.1080/01944366908977225.

Atkinson, P., Hammersley, M., 1994. Ethnography and participant observation. Handbook of Qualitative Research. Sage Publications, Inc, Thousand Oaks, CA, US, pp. 248–261.

Ballweber, J.A., 2006. A comparison of IWRM frameworks: the United States and South Africa. J. Contemp. Water Res. Educ. 135, 74–79. https://doi.org/10.1111/j.1936-704X.2006.mp135001009.x.

Bellamy, J., Ross, H., Ewing, S., Meppem, T., 2002. Integrated Catchment Management: Learning from the Australian Experience for the Murray-Darling Basin. CSIRO Sustainable Ecosystems, Canberra.

Berkes, F., 1994. Co-management: Bridging the two solitudes. 22, 18–20.

Blowers, A., 2017. The Limits of Power: the Politics of Local Planning Policy. Elsevier.

Bracken, L.J., Bulkeley, H.A., Whitman, G., 2015. Transdisciplinary research: understanding the stakeholder perspective. J. Environ. Plann. Manag. 58, 1291–1308. https://doi.org/10.1080/09640568.2014.921596.

Bracken, L.J., Oughton, E.A., Donaldson, A., Cook, B.R., Forrester, J., Spray, C., Cinderby, S., Passmore, D., Bissett, N., 2016. Flood risk management, an approach to managing cross-border hazards. Nat. Hazards. https://doi.org/10.1007/s11069-016-2284-2.

Butterworth, J., Warner, J.F., Moriarty, P., Smits, S., Batchelor, C., 2010. Finding practical approaches to integrated water resources management. Water Altern 3, 68–81.

Charmaz, K., 2011. A constructivist grounded theory analysis of losing and regaining a valued self. In: Wertz, F.J. (Ed.), Five Ways of Doing Qualitative Analysis: Phenomenological Psychology, Grounded Theory, Discourse Analysis, Narrative Research, and Intuitive Inquiry. Guilford Press, New York, pp. 165–204.

Clark, A., Emmel, N., 2008. Walking interviews: more than walking and talking. In: Presented at the 'Peripatetic Practices': a Workshop on Walking, London.

Collins, K., Blackmore, C., Morris, D., Watson, D., 2007. A systemic approach to managing multiple perspectives and stakeholding in water catchments: some findings from three UK case studies. Environ. Sci. Policy 10, 564–574. Social Learning: an alternative policy instrument for managing in the context of Europe's water. https://doi.org/10.1016/j.envsci.2006.12.005.

Collins, K., Ison, R., 2009. Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. Environ. Policy Gov. 19, 358–373. https://doi.org/10.1002/eet.523.

Cook, B.R., Atkinson, M., Chalmers, H., Comins, L., Cooksley, S., Deans, N., Fazey, I., Fenemor, A., Kesby, M., Litke, S., Marshall, D., Spray, C., 2013a. Interrogating participatory catchment organisations: cases from Canada, New Zealand, Scotland and the Scottish–English Borderlands. Geogr. J. 179, 234–247. https://doi.org/10.1111/j.1475-4959.2012.00492.x.

Cook, B.R., Kesby, M., Fazey, I., Spray, C., 2013b. The persistence of “normal” catchment management despite the participatory turn: exploring the power effects of competing frames of reference. Soc. Stud. Sci. 43, 754–779. https://doi.org/10.1177/0306312713478670.

Cook, H., Benson, D., Inman, A., Jordan, A., Smith, L., 2012. Catchment management groups in England and Wales: extent, roles and influences. Water Environ. J. 26, 47–55. https://doi.org/10.1111/j.1747-6593.2011.00262.x.

Cope, M., Elwood, S., 2009. Introduction: qualitative GIS: forging mixed methods through representations, analytical innovations, and conceptual engagements. In: Cope, M., Elwood, S. (Eds.), Qualitative GIS: a Mixed Methods Approach. Sage, Thousand Oaks, CA, pp. 1–12.

Defra, 2016. Catchment Partnerships Action Fund: Environment Agency Report 2015-16. Defra, London.

Defra, 2013. Catchment Based Approach: Improving the Quality of Our Water Environment - a Policy Framework to Encourage the Wider Adoption of an Integrated Catchment Based Approach to Improving the Quality of Our Water Environment (No. PB 13934). Defra, London.

Dekens, J., 2007. Local Knowledge for Disaster Preparedness: a Literature Review. International Centre for Integrated Mountain Development, Kathmandu.

Dungumaro, E.W., Madulu, N.F., 2003. Public participation in integrated water resources management: the case of Tanzania. Phys. Chem. Earth Parts ABC 28, 1009–1014. https://doi.org/10.1016/j.pce.2003.08.042.

Eden, S., 1996. Public participation in environmental policy: considering scientific, counter-scientific and non-scientific contributions. Publ. Understand. Sci. 5, 183–204. https://doi.org/10.1088/0963-6625/5/3/001.

Environment Agency, 2018. Catchment Data Explorer - Twizell Burn from Source to Cong Burn. [WWW Document]. EA Catchment Plan. Linked Data Portal. URL. http://environment.data.gov.uk/catchment-planning/WaterBody/GB103024077590 (accessed 3.26.18).

Environment Agency, 2015. Catchment Partnerships in Operation.

Evans, J., Jones, P., 2011. The walking interview: methodology, mobility and place. Appl. Geogr. 31, 849–858. https://doi.org/10.1016/j.apgeog.2010.09.005.

Fenemor, A., Phillips, C., Allen, W., Young, R., Harmsworth, G., Bowden, B., Basher, L., Gillespie, P., Kilvington, M., Davies-Colley, R., Dymond, J., Cole, A., Lauder, G., Davie, T., Smith, R., Markham, S., Deans, N., Stuart, B., Atkinson, M., Collins, A., 2011. Integrated catchment management — interweaving social process and science knowledge. N. Z. J. Mar. Freshw. Res. 45, 313–331. https://doi.org/10.1080/00288330.2011.593529.

Fischer, F., 2000. Citizens, Experts, and the Environment: the Politics of Local Knowledge. Duke University Press, Durham, NC.

Fritsch, O., 2017. Integrated and adaptive water resources management: exploring public participation in the UK. Reg. Environ. Change 17, 1933–1944. https://doi.org/10.1007/s10113-016-0973-8.

Gobo, G., 2011. Ethnography. In: Silverman, D. (Ed.), Qualitative Research. SAGE, London.

Greening the Twizell Partnership, Personal Communication. Greening the Twizell Partnership Agreement.

Groundworks NE, Cumbria, 2015. Twizell Burn Green Infrastructure Action Plan. Groundworks NE & Cumbria, Annfield Plain.

Harris, R., 2013. The catchment based approach. In: Presented at the IAH Conference on Groundwater and Catchment Management, Unpublished, Tullamore. https://doi.org/10.13140/2.1.5152.2246.

Hayward, C., Simpson, L., Wood, L., 2004. Still left out in the cold: problematising participatory research and development. Sociol. Rural. 44, 95–108. https://doi.org/10.1111/j.1467-9523.2004.00264.x.

Jarvis, A.P., Younger, P.L., 1999. Design, construction and performance of a full-scale compost wetland for mine-spoil drainage treatment at quaking Houses. Water Environ. J. 13, 313–318. https://doi.org/10.1111/j.1747-6593.1999.tb01054.x.

Jemberu, W., Baartman, J.E.M., Fleskens, L., Ritsema, C.J., 2018. Participatory assessment of soil erosion severity and performance of mitigation measures using stakeholder workshops in Koga catchment, Ethiopia. J. Environ. Manag. 207, 230–242. https://doi.org/10.1016/j.jenvman.2017.11.044.

Jones, P., Bunce, G., Evans, J., Gibbs, H., Hein, J.R., 2008. Exploring space and place with walking interviews. J. Res. Pract. 4, 2.

Jones, P., Evans, J., 2012. The spatial transcript: analysing mobilities through qualitative GIS. Area 44, 92–99. https://doi.org/10.1111/j.1475-4762.2011.01058.x.

Kemp, P., Griffiths, J., 1999. Quaking Houses: Art, Science and the Community; a Collaborative Approach to Water Pollution. Jon Carpenter; distributor, Paul and Company, Charlbury, Oxfordshire, England: Concord, MA.

Kilvington, M., Allen, W., Fenemor, A., 2011. Three frameworks to understand and manage social processes for integrated catchment management. N. Z. J. Mar. Freshw. Res. 45, 541–555. https://doi.org/10.1080/00288330.2011.593182.

Kirk, E.A., Reeves, A.D., Blackstock, K.L., 2007. Path dependency and the implementation of environmental regulation. Environ. Plann. C Govern. Pol. 25, 250–268. https://doi.org/10.1068/c0512j.

Knigge, L., Cope, M., 2006. Grounded visualization: integrating the analysis of qualitative and quantitative data through grounded theory and visualization. Environ. Plann. A 38, 2021–2037. https://doi.org/10.1068/a37327.

Kusenbach, M., 2003. Street phenomenology: the go-along as ethnographic research tool. Ethnography 4, 455–485. https://doi.org/10.1177/146613810343007.

Landmark Chambers, 2014. Consultation: the Legal Requirements.

Lane, S.N., 2012. Ethical risk management, but without risk communication? In: Kearnes, M., Klauser, F.R., Lane, S.N. (Eds.), Critical Risk Research Practices, Politics, and Ethics. Wiley, Hoboken, N.J.

Lane, S.N., Odoni, N., Landström, C., Whatmore, S.J., Ward, N., Bradley, S., 2011. Doing flood risk science differently: an experiment in radical scientific method. Trans. Inst. Br. Geogr. 36, 15–36. https://doi.org/10.1111/j.1475-5661.2010.00410.x.

Lerner, D.N., Zheng, C., 2011. Integrated catchment management: path to enlightenment. Hydrol. Process. 25, 2635–2640. https://doi.org/10.1002/hyp.8064.

Margerum, R.D., 1999. Integrated environmental management: the foundations for successful practice. Environ. Manag. 24, 151–166. https://doi.org/10.1007/s002679900223.

Marshall, K., Blackstock, K.L., Dunglinson, J., 2010. A contextual framework for understanding good practice in integrated catchment management. J. Environ. Plann. Manag. 53, 63–89. https://doi.org/10.1080/09640560903399780.

McCall, M.K., 2008. Participatory Mapping and Participatory GIS (PGIS) for CRA, Community DRR and Hazard Assessment.

Mees, H., Suykens, C., Crabbé, A., 2017. Evaluating conditions for integrated water resource management at sub-basin scale. A comparison of the flemish sub-basin boards and Walloon river contracts. Environ. Policy Gov. 27, 59–73. https://doi.org/10.1002/eet.1736.

Ministry of Housing, Communities & Local Government, 2017. Consultation and Pre-decision Matters.

Mitchell, B., Hollick, M., 1993. Integrated catchment management in Western Australia:

transition from concept to implementation. Environ. Manag. 17, 735–743. https://doi.org/10.1007/BF02393894.
Mouratiadou, I., Moran, D., 2007. Mapping public participation in the water framework directive: a case study of the pinios river basin, Greece. Ecol. Econ. 62, 66–76. https://doi.org/10.1016/j.ecolecon.2007.01.009.
Newig, J., Challies, E., Jager, N., Kochskämper, E., 2014. What role for public participation in implementing the EU floods directive? A comparison with the water framework directive, early evidence from Germany and a research agenda. Environ. Policy Govern. 24, 275–288. https://doi.org/10.1002/eet.1650.
Nones, M., 2015. Implementation of the floods directive in selected EU member states: implementation of the floods directive. Water Environ. J. 29, 412–418. https://doi.org/10.1111/wej.12129.
Plummer, R., FitzGibbon, J., 2004. Some observations on the terminology in co-operative environmental management. J. Environ. Manag. 70, 63–72. https://doi.org/10.1016/j.jenvman.2003.10.005.
Pomeroy, R.S., Berkes, F., 1997. Two to tango: the role of government in fisheries co-management. Mar. Pol. 21, 465–480. https://doi.org/10.1016/S0308-597X(97)00017-1.
Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. Biol. Conserv. 141, 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014.
Robins, L., Burt, T.P., Bracken, L.J., Boardman, J., Thompson, D.B.A., 2017. Making water policy work in the United Kingdom: a case study of practical approaches to strengthening complex, multi-tiered systems of water governance. Environ. Sci. Pol. 71, 41–55. https://doi.org/10.1016/j.envsci.2017.01.008.
Rouillard, J.J., Spray, C.J., 2017. Working across scales in integrated catchment management: lessons learned for adaptive water governance from regional experiences. Reg. Environ. Change 17, 1869–1880. https://doi.org/10.1007/s10113-016-0988-1.
Sabatier, P.A., 1986. Top-down and bottom-up approaches to implementation research: a critical analysis and suggested synthesis. J. Publ. Pol. 6, 21–48.
Schild, R., 2018. Fostering environmental citizenship: the motivations and outcomes of civic recreation. J. Environ. Plann. Manag. 61, 924–949. https://doi.org/10.1080/09640568.2017.1350144.
Starkey, E., Parkin, G., 2015. Community Involvement in UK Catchment Management: a Review of Current Knowledge (No. FR/R0021). Foundation for Water Research, Marlow.
Stringer, L.C., Reed, M.S., 2007. Land degradation assessment in Southern Africa: integrating local and scientific knowledge bases. Land Degrad. Dev. 18, 99–116. https://doi.org/10.1002/ldr.760.
Tritter, J.Q., McCallum, A., 2006. The snakes and ladders of user involvement: moving beyond Arnstein. Health Pol. 76, 156–168. https://doi.org/10.1016/j.healthpol.2005.05.008.
Varis, O., Enckell, K., Keskinen, M., 2014. Integrated water resources management: horizontal and vertical explorations and the 'water in all policies' approach. Int. J. Water Resour. Dev. 30, 433–444. https://doi.org/10.1080/07900627.2014.912130.
Voulvoulis, N., Arpon, K.D., Giakoumis, T., 2017. The EU Water Framework Directive: from great expectations to problems with implementation. Sci. Total Environ. 575, 358–366. https://doi.org/10.1016/j.scitotenv.2016.09.228.
Warner, J., 2011. Flood Planning the Politics of Water Security. I.B. Tauris, London.
Warner, J.F., 2006. More sustainable participation? Multi-Stakeholder platforms for integrated catchment management. Int. J. Water Resour. Dev. 22, 15–35. https://doi.org/10.1080/07900620500404992.
Waterton, C., Maberly, S.C., Norton, L.R., Tsouvalis, J., Watson, N.M., Winfield, I.J., 2011. A Community Approach to Catchment Management (No. 32), Rural Economy and Land Use Policy and Practice Note Series. Rural Economy and Land Use Programme, Lancaster.
Watson, N., 2014. IWRM in England: bridging the gap between top-down and bottom-up implementation. Int. J. Water Resour. Dev. 30, 445–459. https://doi.org/10.1080/07900627.2014.899892.
Watson, N., Deeming, H., Treffny, R., 2009. Beyond bureaucracy? Assessing Institutional Change in the Governance of Water in England 2, 13.
Watson, N., Howe, J., 2006. Implementing the EU water framework directive: experiences of participatory planning in the ribble basin, north west England. Water Int. 31, 472–487. https://doi.org/10.1080/02508060608691951.
Whitman, G.P., Pain, R., Milledge, D.G., 2015. Going with the flow? Using participatory action research in physical geography. Prog. Phys. Geogr. https://doi.org/10.1177/0309133315589707.
Wynne, B., 1996. May the sheep safely graze? A reflexive view of the expert-lay knowledge divide. In: Lash, S., Szerszynski, B., Wynne, B. (Eds.), Risk, Environment and Modernity: towards a New Ecology, Theory, Culture & Society. Sage Publications, London; Thousand Oaks, Calif.
Young, O., 2006. Vertical interplay among scale-dependent environmental and resource regimes. Ecol. Soc. 11. https://doi.org/10.5751/ES-01519-110127.

Journal of Hydrology 562 (2018) 267–280

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

The importance of volunteered geographic information for the validation of flood inundation models

E. Rollason[a,*], L.J. Bracken[a], R.J. Hardy[a], A.R.G. Large[b]

[a] Department of Geography, Durham University, Durham DH1 3LE, United Kingdom
[b] School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom

ARTICLE INFO

This manuscript was handled by G. Syme, Editor-in-Chief, with the assistance of Heather M. Smith, Associate Editor

Keywords:
Flooding
Hydraulic modelling
Model validation
Volunteered geographic information
Citizen science

ABSTRACT

Two dimensional flood inundation models capable of simulating complex spatially and temporally differentiated floodplain flows are routinely used to model and predict flooding. However, advances in modelling techniques have not been matched by improvements in model validation. Validation of flood models remains challenging due to a lack of available spatially-explicit data; traditionally measured data and validation approaches reveal little about the ability of a model to simulate the complex dynamics of floodplain flows, including the pathways, timeline, and impacts of an event. In this paper we propose a novel method for the validation of hydraulic models of flooding using quantitative and qualitative Volunteered Geographic Information (VGI). This method uses VGI data to enhance traditionally measured validation data by reconstructing the observed dynamics of a flood, allowing validation of the temporal and spatial simulation of these dynamics. We illustrate the method using a case study from Corbridge in the northeast of England, using VGI collected through participatory research with people affected by severe flooding in 2015. The results of the study demonstrate that VGI data can be used for the effective reconstruction of flood event dynamics. The results also reveal that the proposed validation approach is able to identify underperformance in the model's simulation of event dynamics not evaluated by standard global performance measures. Such a lack of evaluation can have adverse consequences where dynamic model outputs are used locally to influence floodplain management. As a result, we propose a new framework for model validation, adopting a pragmatic and flexible approach to examining event dynamics using a diverse range of data.

1. Introduction

Flooding is one of the most serious environmental hazards globally, with flooding the cause of almost 50% of all economic losses resulting from natural hazards (Munich Re, 2013); and losses are likely to increase under climate change as flooding is exacerbated (Hirabayashi et al., 2013; Reynard et al., 2017). The need to better understand current and future flood risks has led to a significant rise in the use of predictive numeric models to understand river processes, including flooding (Bates and De Roo, 2000; Hunter et al., 2007; Lane et al., 2011a; Parkes et al., 2013). The availability of high quality, spatially-distributed data on river environments (Cobby et al., 2003) means two dimensional models, capable of explicitly simulating complex, spatially and temporally-differentiated floodplain flows are now a standard approach in many fields, including the insurance industry (Bates and De Roo, 2000; Bradbrook et al., 2004; Hunter et al., 2007; Néelz and Pender, 2013; Teng et al., 2017). However, improvements in data, and advances in numerical modelling techniques, have not been matched by improvements in the validation of these models; the process by which we can assess whether our models agree with observations (Refsgaard and Henriksen, 2004). Established approaches to validation are typically spatially or temporally limited in scope by the availability of accurate datasets.

This paper seeks to address gaps in our existing data and practices of model validation. Using a case study from northeast England, we propose a new approach, which builds on existing statistical methods of comparison against observed data. We demonstrate that, by exploiting diverse, volunteered and crowd-sourced datasets, we can both spatially and temporally reconstruct the key dynamics of flood events. The approach demonstrates how alternative data-sources can be used to enhance existing data, providing information on flooding processes for which traditionally regarded data is rarely available. Finally, the approach offers a more holistic validation of the complex dynamics of floodplain flows, including the pathways, timeline, and impacts of events.

* Corresponding author at: Department of Geography, Science Laboratories, Durham University, South Rd, Durham DH1 3LE, United Kingdom.
E-mail address: e.d.rollason@durham.ac.uk (E. Rollason).

https://doi.org/10.1016/j.jhydrol.2018.05.002
Received 30 November 2017; Received in revised form 23 April 2018; Accepted 2 May 2018
Available online 04 May 2018

2. Application of volunteered geographic information in hazard assessment

2.1. VGI data in disaster risk reduction

Paucity of measured data on disasters, including floods, is common in the field of Disaster Risk Reduction (DRR). To address this issue, research has explored the use of non-standard, unscientific datasets derived from local communities within a disaster zone (Goodchild and Glennon, 2010). One data source being explored within DRR research is Volunteered Geographic Data (VGI: (Haklay et al., 2014)), defined as 'the widespread engagement of large numbers of private citizens, often with little in the way of formal qualifications, in the creation of geographic information' (Goodchild, 2007, p. 212). VGI datasets include any geo-located information on a disaster, and can comprise a diverse range of data including personal accounts, photographs and videos, and crowd-sourced measurements (Hung et al., 2016; McDougall, 2012; Triglav-Cekada and Radovan, 2013).

The use of VGI datasets has been demonstrated across a wide range of studies of hazard events (for systematic reviews of the current research base see Granell and Ostermann, 2016; and Klonner et al., 2016). For floods, the use of VGI data has been demonstrated across a range of applications. For instance, McCallum et al. (2016) utilised VGI to improve the availability of pre-event data on flood vulnerability in data-sparse regions, demonstrating how crowd-sourced information can enhance mapping for emergency responders after disasters. A number of studies have also explored the potential for collecting VGI datasets to inform real-time disaster response. For example, Wan et al. (2014) at a global scale, and Degrossi et al. (2014) and Horita et al. (2015), both working at city scale in Brazil, demonstrated cloud-based systems for the collection and processing of VGI flooding data. These systems synthesised diverse flooding datasets, providing real-time information for emergency response and developed a long-term database of information on historic floods. VGI has also been used in the post-event phase: Schnebele and Cervone (2013) and Triglav-Cekada and Radovan (2013) utilised VGI flooding imagery collected after the event to improve flood maps derived from satellite imagery. Such research demonstrates how the VGI data can provide spatially distributed information on even large flood events, and how it can also be used to validate remotely-sensed hazard maps at a local scale.

While these examples demonstrate the emerging, widespread application of VGI for disaster preparedness and response, they also demonstrate how limited and fragmented the use of VGI data is for many applications; reflecting the non-standard nature of the data. McCallum et al. (2016) use only participatory mapping for their vulnerability assessment, whilst Schnebele and Cervone (2013) and Triglav-Cekada and Radovan (2013) use only imagery for their flood mapping analysis. Wan et al. (2014), Degrossi et al. (2014), and Horita et al. (2015) collected a wider range of data, including citizen reports of flooding, but highlighted significant problems utilising such diverse datasets which cannot be automatically processed. Other criticisms of VGI datasets often focus on issues of data validity or the difficulties of assessing data quality in the absence of traditionally-measured data sources (Hung et al., 2016; Muller et al., 2015). As a result, many studies use collection of VGI data as an adjunct to traditional data, rather than as a source of data in its own right or as a standalone method for the creation of new knowledge about specific hazards such as flooding (Usón et al., 2016).

2.2. Emerging practices of engagement

In contrast to the VGI projects noted in Section 2.1, citizen science and citizen observatory programmes represent moves towards establishing new practices of geo-spatial knowledge co-creation. These efforts are driven by the need for greater public participation in environmental decision-making (National Research Council, 2008) laid out in the Aarhus Convention (Lee and Abbot, 2003) and the European Floods Directive (Wehn et al., 2015). Citizen science and citizen observatories have been demonstrated across a range of disciplines including flooding and hydrology (Lanfranchi et al., 2014; Muller et al., 2015; Ruiz-Mallén et al., 2016; Starkey et al., 2017), and research has begun to demonstrate how citizen-led, locally collected data can provide valuable information for enhancing our understanding of catchment processes and planning catchment interventions (Starkey et al., 2017). In contrast to the often *ad-hoc* collection of VGI data, citizen science typically involves engaged and trained participants and rigid data collection frameworks to help overcome issues of data validity (Wiggins and He, 2016).

However, an issues arises: flood events, in common with other disasters, represent situations in which data can often only be collected in an *ad-hoc* fashion, as the presence of local volunteers able and willing to collect data cannot be guaranteed (Starkey et al., 2017). This is particularly relevant as citizen science programmes are often limited to small numbers of participants (Baruch et al., 2016), meaning drop-outs during an event would have a greater impact on the data collected. Efforts therefore need to be made to understand how we can integrate the opportunities for large scale engagement represented by VGI with the opportunities for local participation, and the improvements in data quality, represented by citizen science. Studies have begun to explore how integrating citizens into activities beyond simple data collection can improve engagement and data quality, for example see Starkey et al. (2017), but in the context of flooding this field is still in its infancy. However, there is obvious potential for a more integrated approach between large scale VGI data collection and the more locally focused nature of citizen science (see Brandeis and Carrera Zamanillo, (2017) for further details).

2.3. Integrating citizen data into the validation of flood inundation models

One situation which potentially offers the opportunity to integrate citizen science and VGI in this way is in the construction and validation of numerical flood inundation models of flood-affected communities. Flood inundation modelling forms a cornerstone of flood risk assessment (Bates and De Roo, 2000; Hunter et al., 2007; Lane et al., 2011a; Parkes et al., 2013). It informs almost all flood management activities, from monitoring and warning systems (Nester et al., 2016), to evacuation planning (Simonovic and Ahmad, 2005) and emergency response (Coles et al., 2017), to the design and construction of future developments (Pappenberger et al., 2007a). However, at present, flood modelling is primarily an expert-led activity with little or no citizen involvement (Lane et al., 2011b).

The established approach to validating inundation model outputs is to match available historical data to simulated outputs (Pappenberger et al., 2007a). The goodness-of-fit between predicted and observed river levels can be assessed using statistical best-fit techniques such as Nash-Sutcliffe Model Efficiency (NSME) (Nash and Sutcliffe, 1970) or Root Mean Square Error (RMSE) (Altenau et al., 2017). Similarly, point-in-time global flood extents can also be assessed using binary performance measures such as the Critical Success Index (C), which compares the extent of simulated inundation to the observed inundation (Wing et al., 2017). What tests are undertaken is dependent upon data availability. In-channel river level data is a source of historical information commonly available in medium and large catchments (Hunter et al., 2007; Parkes et al., 2013). To examine out of bank inundation, high resolution aerial and satellite imagery (Renschler and Wang, 2017), multiband remote sensing such as LANDSAT (Fernández et al., 2016; Jung et al., 2014), or other sensors such as Synthetic Aperture Radar (García-Pintado et al., 2013; Pappenberger et al., 2007b; Wood et al., 2016) can all be used. Studies have also demonstrated the usefulness of ground observations of wrack and water marks in reconstructing maximum inundation extents and levels, (Neal et al., 2009; Parkes et al., 2013; Segura-Beltrán et al., 2016). However, collection of this latter form of flood inundation evidence typically requires post-event surveys which are time and resource consuming and often yield spatially limited results (Segura-Beltrán et al., 2016).

The validation of model outputs is therefore constrained by data availability to being either spatially or temporally limited: gauged river levels may record levels throughout an event but are limited to discrete locations; whilst remote sensing can provide spatially extensive information on inundation but only at discrete time points. Consequently, established statistical techniques for model validation have been unable to assess the effectiveness of models in simulating both spatial **and** temporal event dynamics (Hunter et al., 2007). These dynamics include the pathways which water takes across the floodplain, the flood timeline, and local variation in flood impacts; all of which are capable of being simulated in detail by current 2D inundation models (Teng et al., 2017). This disparity between the complexity of current inundation models and the relative lack of data against which to test them represents an opportunity to integrate citizen-collected data into existing, expert-led practices of knowledge creation. Thus far however, there has been little exploration of this issue.

3. Methods

In this research we build on the methodology used by Smith et al. (2012) by demonstrating how VGI data should be used more routinely for model validation as a dataset in its own right. Smith et al. (2012) provide a demonstration of the use of a diverse VGI database to construct and validate a model of coastal flood defence overtopping. They utilise VGI to build the model, by using locally recorded locations of flood defence overtopping as point inflows into the model domain. They also validate its outputs, reconstructing the observed flood extents and depths at properties using historical photographs and media accounts. However, the approach demonstrated was limited by the data used, which was confined to imagery and records of depth at specific locations. By examining only modelled extent and depth, the method provides a spatial but not a temporal validation. The resultant model cannot examine the functioning of the model in simulating flood dynamics in more detail, nor does the study explore how VGI could be used more comprehensively. This is reflected in Smith et al.'s conclusion that the data used represented "*useful **corroborating** evidence for the performance of the model*" (p. 43), after a more traditional validation using available measured data.

In this study we develop an experimental validation methodology which uses a wide range of data potentially available through VGI and participatory research approaches to examine different aspects of a simulation output. To demonstrate the method we use a database of VGI to reconstruct in detail a severe flood in the northeast of England, and use a VGI-based flood reconstruction to validate the outputs of a 2D flood inundation model of the event. Finally, we compare the outputs to more established methods of validation to demonstrate the success of the method.

3.1. Model build

We utilised the flood inundation model LISFLOOD-FP to produce simulated flood event outputs for our case study. LiSFLOOD-FP is a 2D finite difference model developed specifically to utilise high resolution topographic data to simulate floodplain dynamics (Bates et al., 2010; Hunter et al., 2005; Neal et al., 2012, 2011; Bates and De Roo, 2000). Although we used LISFLOOD-FP here, the validation approach developed should be considered generic, and is designed to be applicable to any 2D model that predicts dynamic floodplain inundation. The principle data requirements for the model are outlined in Table 1.

3.1.1. The case study: The 2015 Corbridge flood

The test case used in this study is the market town of Corbridge, located in the Tyne Valley in the northeast of England (Fig. 1). Corbridge was chosen to develop and test the experimental validation because of its recent history of severe flooding and the way its population were already engaged with ongoing flood research (Rollason et al., 2018).

Corbridge experienced extensive flooding when Storm Desmond resulted in record rainfall across areas of the north of England (Barker et al., 2016) on 5th December 2015. The flood, an event with a return period estimated to be between 100 and 200 years (Marsh et al., 2016), overtopped the flood defences at Corbridge, and inundated 70 properties on the south side of the River Tyne (Environment Agency, 2016).

Using LiSFLOOD-FP a model of the River Tyne was constructed, extending for approximately 30 km, with Corbridge situated approximately half way down the modelled reach. Fig. 1 shows the modelled reach and the main data used are discussed in Table 1. To predict the December 2015 flood event, the model was run for a 72 h period starting at 12:00 on Friday 4th December continuing until 12:00 on Monday 7th December. This period covered both the rising and falling limbs of the main hydrograph at Corbridge. Simulation results were generated for every 15 min period, predicting flood depths, flood velocity, and time of inundation.

3.2. Validating the model outputs using established approaches

Initial verification and calibration of the model was undertaken during the model build. The mesh resolution independence of the model was verified by testing against DEM resolutions of 5.0, 7.5, 10.0, and 20.0 m (Hardy et al., 1999; Horritt and Bates, 2001). The model was further calibrated against floodplain friction values, which were estimated from Chow (1959) based on satellite imagery and field visits. Differential friction values were applied to the channel of the Tyne and the main floodplain, with the area of the channel delineated based on satellite imagery. Manning's values for floodplain friction between 0.02 and 0.06 ($m^{1/3}\,s^{-1}$) and channel friction values between 0.03 and 0.07 ($m^{1/3}\,s^{-1}$) were used in the model calibration runs, validation of which was undertaken using established statistical approaches. Validation was also undertaken on the calibrated model as a baseline against which to test the effectiveness of the experimental methodology.

Two datasets were available for the validation using established statistical techniques: gauged river levels and observed flood extents for the estimated maximum extent. Gauged river levels were validated using both Nash-Sutcliffe Model Efficiency (NSME) and Root Mean Square Error (RMSE) (Altenau et al., 2017). Maximum flood extents were validated using the Critical Success Index (C) (Wing et al., 2017; Wood et al., 2016), sometimes referred to as the 'fit statistic' (Sampson et al., 2015). C tests the proportion of wet observed data that is replicated by the model on a per-pixel basis, accounting for both over- and under-prediction:

$$C = \frac{M_1O_1}{M_1O_1 + M_0O_1 + M_1O_0}$$

where M is the modelled outcome and O is the observed outcome, and 1 or 0 represents pixels that are either wet or dry. C can range from 0 (no match between simulated and observed inundation) to 1 (perfect match between simulated and observed inundation).

3.3. Developing a new solution for validating inundation models

3.3.1. The Volunteered Geographic information database

Participatory research in Corbridge was undertaken with the community at to develop a VGI database of local knowledge and experiences of the December 2015 flooding event. As part of wider participatory work being undertaken at Corbridge (see Rollason et al., 2018) we carried out two participatory mapping workshops with 10 research participants, and five individual walking interviews, after Evans and Jones (2011). Discussions and interviews were un- or semi-structured in nature (Dowling et al., 2016), with participants being encouraged to lead the discussion and discuss their own knowledge and experiences.

Table 1
The principle data requirements of the LiSFLOOD-FP model and the data used in the construction of a model for this study.

Model component	Data required	Data Used in the study
Topography	Pre-processed, 'bare-earth' raster grid of topography with buildings and vegetation removed	Environment Agency 2 m horizontal resolution 'bare earth' LiDAR data, resampled using averaging technique Structures, e.g. bridges and flood defences, added to the DEM prior to inclusion in the model
Inflow conditions	Stage or discharge inflows	Point inflows from Environment Agency gauging stations at 15 min temporal resolution
Outflow conditions	A downstream boundary derived from either gauged river levels or a free flow boundary	Free flow boundary using slope calculated from local DEM values
Floodplain friction parameters	A raster grid representing Manning's 'n' values for different landcover classes	Values estimated from Chow (1959) based on satellite imagery and field visits

During the mapping workshops participants were encouraged to locate their knowledge on blank maps of the study area, for example observed locations of defence overtopping or pathways of flood water flow. Walking interviews were also participant-led following either the natural go-along (Kusenbach, 2003), or participatory walking interview (Clark and Emmel, 2008) models. Spatial data were recorded either directly into GIS or onto paper maps for later digitisation. Verbal discussions were recorded and analysed by adopting a grounded theory approach (Charmaz, 2011), combining both the audio recording and visual representations (Knigge and Cope, 2006). Information provided in anecdotal accounts was triangulated with digital images and video taken during the event and collected during the participatory process.

The information were used to produce an extensive database of how the flood occurred (Table 2). Most of the data was collected from the local community but it was augmented by (non-georeferenced) footage from an unmanned aerial vehicle (UAV) identified on news footage immediately after the event, and collected by a local UAV enthusiast.

3.3.2. Using the VGI database to reconstruct the dynamics of a severe flood

During validation it is necessary to establish the main dynamics of the flooding event for which the model is being validated. To do this, we divided the VGI data into three information categories:

1. *Pathways* – data which provided information on the movement of flood water through the study area, including areas of overtopping and principle flow directions.
2. *Impacts* – data which provided information on the maximum extent of the flooding.

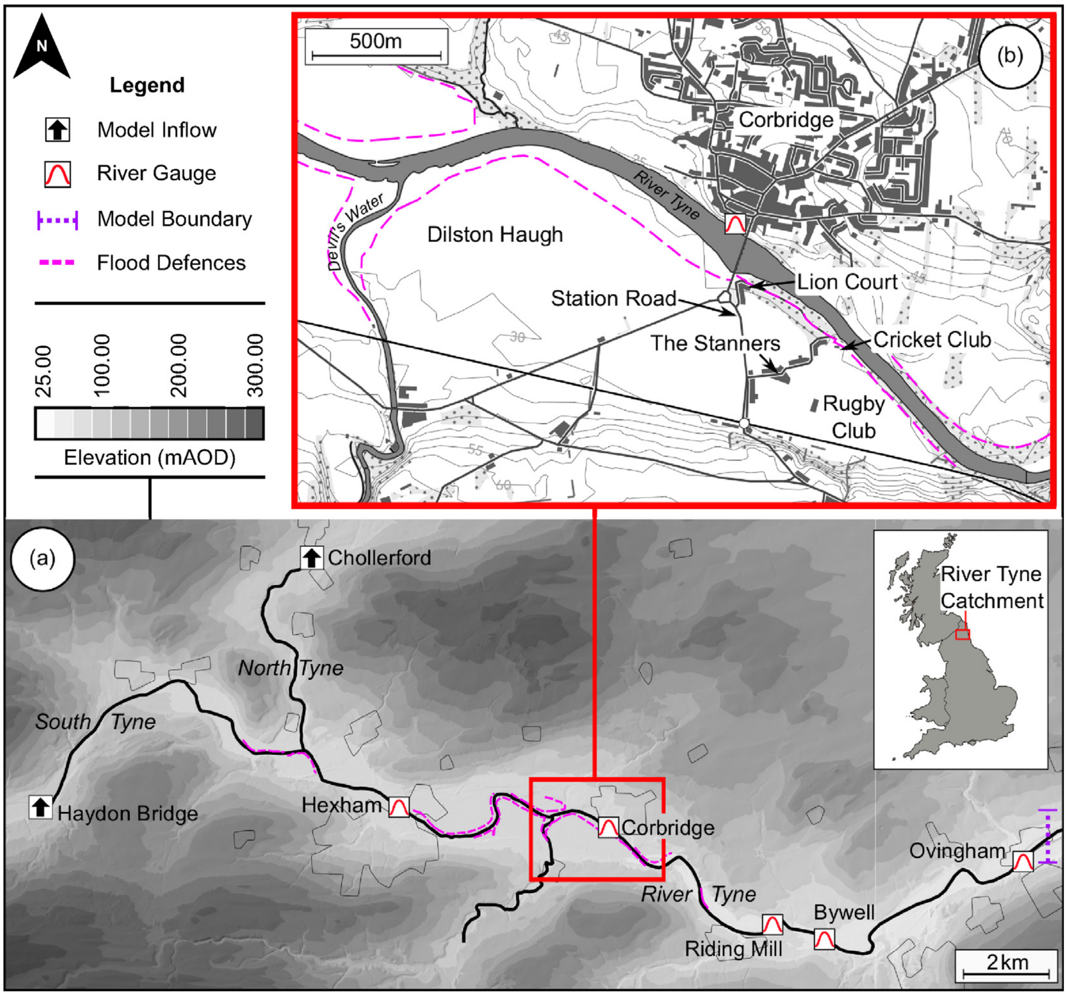


Fig. 1. (a) The modelled reach showing the key elements of the model and the locations of the boundary conditions used. (b) the Corbridge study area and locations referred to in the text.

Table 2
VGI data used for reconstruction of the December 2015 flood event. Data was collected between April and May 2016.

Data Type	Source	Quantity
Personal accounts	• Interviews and correspondence with individual members of the Corbridge Flood Action Group	5
Mapped data	• Group mapping workshops undertaken with members of the Corbridge Flood Action Group	Outputs from two group mapping workshops
Photographs	• Photographs taken during or immediately after the flooding event showing flood pathways or impacts, e.g. areas of gravel deposition or wrack lines, contributed by members of the Corbridge Flood Action Group	18
	• Photographs taken after the event by the researchers showing impacts e.g. wrack lines	
Video	• Videos taken during the flood event by members of the Corbridge Flood Action Group	2
	• Videos taken by UAV immediately after the flooding event and obtained through correspondence with research participants.	2 – one taken 24hrs after the peak of the flood and one 48hrs after the peak of the flood

3. *Timeline* – data which provided information on the timing of key events during the flood, including overtopping of defences, arrival of flood water at key locations, and inundation of properties.

Mapped data and personal accounts (anecdotal data) were combined into a single vector layer within a GIS, with the anecdotal data included within the layer as specific or linked attribute data following the qualitative GIS approaches of Cope and Elwood (2009). This layer was used to reconstruct a unified account of the event dynamics, including times of overtopping and inundation of properties. Photographs and videos were georeferenced and quantitative information was extracted where possible, for example the location of wrack or height of flood marks, or the direction of gravel deposition showing flow pathways. Where quantitative data was not collected directly, images were used simply for interpretation and to validate other data sources. Perks et al. (2016) have demonstrated how georeferenced UAV data can allow precise quantification of flood flows and flow vectors for an urban situation in Scotland. However, the UAV footage collected during the Corbridge study was obtained opportunistically and as a result did not contain the necessary metadata or ground control point information to allow it to be georeferenced. It was thus used in an analytical manner: using darker surface colours or isolated water bodies to indicate previous areas of inundation (Renschler and Wang, 2017). In areas where no footage was available, interpolation of the flood extent was undertaken based on expert judgement and using LiDAR topography.

3.3.3. *Quality control of VGI data*

The VGI dataset collected for this study is fragmentary and 'format-messy'. This makes the assessment of data quality using traditional quantitative measures difficult. However, it is still necessary to assess the extent to which we can have confidence in the data and the flood event reconstruction derived from it and, to do this, we adopted the approach of Mays and Pope (2000). This validation approach uses a researcher-led, reflexive approach relying on triangulation of different data sources to assess and validate individual pieces of information; for example the comparison of anecdotal accounts with imagery or physical evidence on the ground. This approach does not provide the quantifiable analysis of error normally required for model validation. Instead, the method identifies areas of error and uncertainty (spatial and temporal), or contested knowledge which can arise due to the nature of the VGI data being used.

3.3.4. *The experimental framework for model validation*

The experimental validation brought together the flood event reconstruction derived from the VGI database with the outputs of the LISFLOOD-FP model which represent the dynamics of the event. The outputs showed dynamic flood depths and flow vectors, times of inundation, and maximum flood extents.

Flood depths and times of inundation were extracted directly from the model at user-defined time-steps in raster grid format. As a velocity output, the model produces grids representing the flow of water between grid cells in both the x and y directions. To convert these velocity

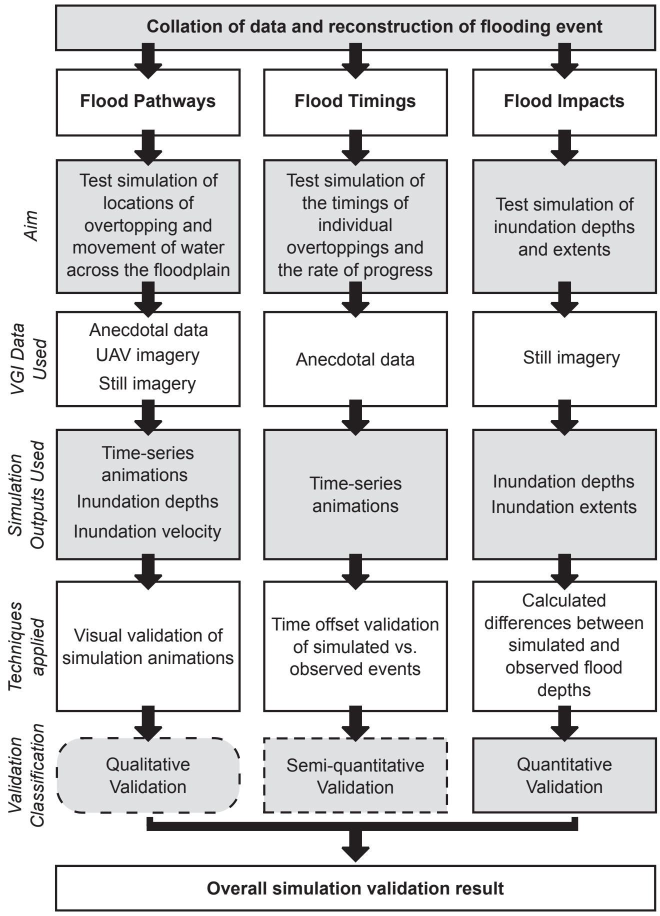


Fig. 2. The experimental approach showing the types of validation which can be applied, depending on the available information and how these correspond to the dynamics of the event. The availability of data and the validation methods adopted influences the nature of the final validation, which represents a blend of qualitative, semi-quantitative, and quantitative data and methods.

grids into flow vectors, the SAGA GIS tool 'Gradient Vectors from Directional Components' (Conrad et al., 2015) was used. An average across 4 grid cells (40 m) was used to reveal underlying flow directions which could be compared against the observed evidence. Fig. 2 shows the experimental approach and the VGI datasets used to validate the different dynamics of the event.

4. Results

4.1. *Calibration and validation of the model outputs using established methods*

Table 3 shows that the model performed consistently well in

Table 3

Results of the calibration and validation of the model using standard statistical techniques. Emboldened and highlighted rows indicate the best performing parameter sets which were used to estimate the parameters for the final model. The calibrated model used Manning's n of 0.03 ($m^{1/3}s^{-1}$) on the floodplain and 0.04 ($m^{1/3}s^{-1}$) in the channel, and a DEM resolution of 10 m.

Parameter Tested			RMSE				NSE (vs Gauge)				C%
			Hexham	Corbridge	Riding Mill	Bywell	Hexham	Corbridge	Riding Mill	Bywell	
	Channel	Floodplain									
Mannings 'n'	0.02	0.03	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.04	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.05	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.06	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.07	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.03	0.03	0.235	0.407	0.370	0.247	0.953	0.944	0.948	0.983	90%
	0.03	0.04	0.354	0.590	0.501	0.385	0.895	0.884	0.904	0.958	89%
	0.03	0.05	0.354	0.590	0.501	0.385	0.895	0.884	0.904	0.958	89%
	0.03	0.06	0.332	0.538	0.456	0.338	0.907	0.903	0.920	0.968	89%
	0.03	0.07	0.319	0.508	0.430	0.312	0.915	0.914	0.929	0.972	89%
	0.04	**0.03**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	0.04	0.233	0.365	0.422	0.332	0.954	0.955	0.932	0.969	90%
	0.04	**0.05**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	**0.06**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	**0.07**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.05	0.03	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
	0.05	0.04	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
	0.05	0.05	0.235	0.348	0.466	0.393	0.954	0.959	0.917	0.956	86%
	0.05	0.06	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
	0.05	0.07	0.319	0.508	0.430	0.312	0.915	0.914	0.929	0.972	89%
	0.06	0.03	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
	0.06	0.04	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
	0.06	0.05	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
	0.06	0.06	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
	0.06	0.07	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
DEM Resolution	5		0.093	0.436	1.271	0.761	0.993	0.936	0.381	0.836	88%
	7.5		0.220	0.435	0.341	0.710	0.959	0.937	0.956	0.857	88%
	10		**0.288**	**0.487**	**0.443**	**0.320**	**0.930**	**0.920**	**0.925**	**0.971**	**89%**
	20		**0.204**	**0.261**	**0.359**	**0.514**	**0.965**	**0.977**	**0.951**	**0.925**	**89%**
			RMSE				NSE				C%
			Hexham	Corbridge	Riding Mill	Bywell	Hexham	Corbridge	Riding Mill	Bywell	
Calibrated Model (Mannings 'n' FP 0.03 Ch 0.04 / DEM resolution 10m)			0.259	0.443	0.335	0.194	0.944	0.934	0.957	0.989	90%

simulating gauged water levels along the whole modelled reach with a floodplain Manning's n of between 0.03 and 0.07 ($m^{1/3}\,s^{-1}$) and a DEM resolution of either 10 or 20 m. This DEM resolution is in line with the recommendations of the UK Environment Agency Fluvial Design Guide (Crower, 2009), which suggests model resolutions of 25 m in rural areas and 10 m for urban areas. It is also in line with other catchment or sub-regional studies, although there is significant variation in the resolutions used (Gobeyn et al., 2017; Neal et al., 2011; Renschler and Wang, 2017; Savage et al., 2016; Wing et al., 2017). Some studies have demonstrated the use of very high resolution topographic information, for example Sampson et al. (2012), but these are exclusively applied to small scale, urban studies rather than the larger, rural reaches such as that simulated in the current study.

Table 3 also indicates the goodness of fit, measured by the Critical Success Index C, between the simulated and observed maximum flood extents within the study area. The results indicate that all of the tested parameter sets achieved greater than 85% success in matching the observed peak flood extents. The calibrated model achieved a 90% success rate, which compares very favourably with other modelling studies which achieved between 50% and 90% success rates (Renschler and Wang, 2017; Wing et al., 2017). At a local scale, visual assessment of the simulated and observed extents (Fig. 3) show that within the area of interest there was considerable variability in areas of over- and underestimation. In particular, the model overestimated the extent of overtopping of the flood defences at Dilston Haugh (Fig. 3 location a) and at the Rugby Club (Fig. 3 location b), whilst it underestimated the extent of flooding on Dilston Haugh. It is considered likely that the bare earth DEM (vegetation and buildings removed) used in the model contained inaccuracies which influenced the flow of water across the floodplain, which will be discussed further below.

4.2. Application of the experimental validation approach

4.2.1. Reconstruction of the 2015 event dynamics

Fig. 4 shows the reconstruction of the dynamics of the December 2015 flood, undertaken using the VGI database. These can be divided into two types of dynamics: pathways of defence overtopping; and pathways of flow across the floodplain. The results indicated three pathways of defence overtopping (FP1, FP3, and FP4). FP1 and FP3 represented generalised overtopping of the defences (the extent of which is indicated on Fig. 4), whereas FP4 was identified as a specific location of overtopping at the junction between two defence types, which resulted in a distinct flow of water onto the Cricket Club from the north.

Two pathways of flow across the floodplain were also reconstructed. FP2 represented a general flow from the upstream areas of overtopping following the topography of the floodplain. FP5 represented backing up of water that was unable to return back to the river as a result of the flood defence and the high water levels in the river. This was manifested in the data as a reported sudden increase in depth at properties between 19:00 and 20:00 GMT on 5th December. Two main areas of impact were also represented at The Stanners (Fig. 4, FI1) and Station Road (Fig. 4, FI2). Although the distribution of properties affected by the flooding event was greater than that shown, no data was available

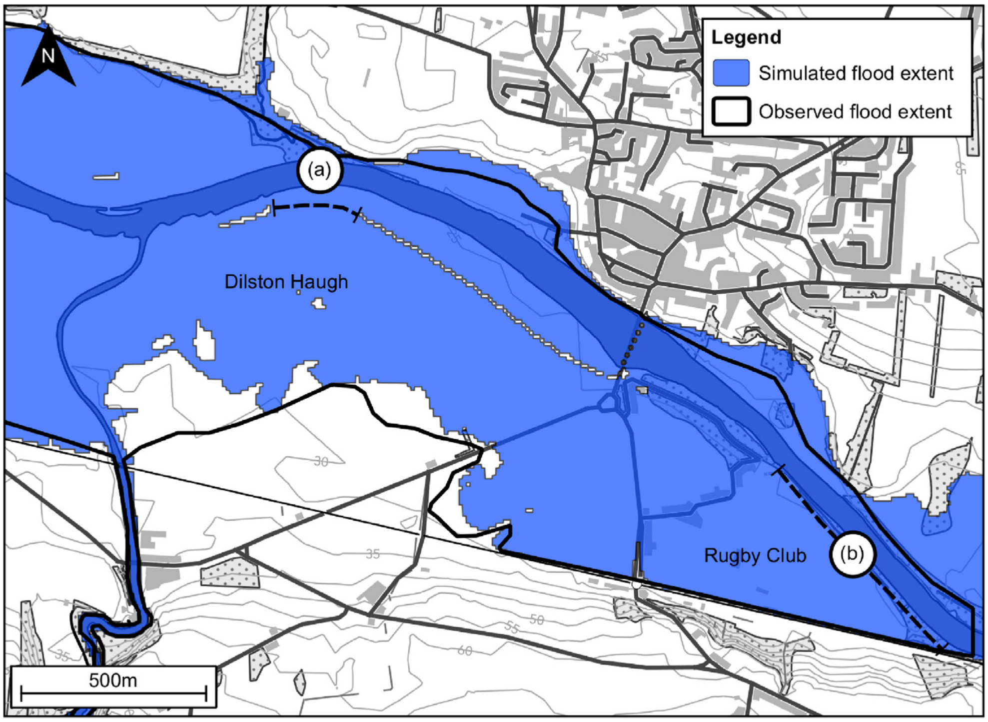


Fig. 3. The predicted maximum flood extent produced by the calibrated model compared to the observed maximum extent derived from analysis of the UAV imagery. The results show that there was some variability in the under- and over-prediction of flooding on both banks. In particular, locations (a) and (b) showed areas of overtopping of the defences which were not observed, indicating that the bare earth DEM used for the model may contain inaccuracies which affected the flow of water across the floodplain.

to validate the impacts in these other areas.

4.3. Results of the experimental validation

The calibrated model was validated against the key pathways, timings and impacts of the December 2015 flood identified in Section 4.2.

4.3.1. Validation of flood pathways

Pathways were identified from the model simulation using 15 min resolution time-series outputs of depth and velocity. Fig. 5 shows the results of the validation. The results indicate that the model was successful in simulating all of the major pathways identified in the observed data. In the case of FP1 and FP2 the model showed general overtopping of the defences along Dilston Haugh and flow following low-lying areas of the floodplain topography, which are potentially relict river channels. This is further north on the floodplain than was interpreted from the VGI, and is considered to reflect error within the VGI rather than in the model. This is because these flow pathways were not directly observed by the research participants; instead they were inferred from the direction of flood waters which entered their homes. For FP3 and FP4 the model showed successful differentiation between the two pathways. FP3 was simulated as overtopping of the wall at Lion Court, and there is also a distinct overtopping location at FP4. This results in flow across the Cricket Club from the north, reported by research participants, which is separate to the other flooding at and around Lion Court.

The processes behind the time-line of FP5 were the most contested within the VGI, with participants reporting a sudden increase in depth at The Stanners and Station Road (Fig. 5), but with considerable disagreement over the pathway this water had taken. Review of the flow vectors produced by the model for this area was not conclusive in identifying a simple backflow of water. However, calculation of the change in simulated inundation depth at The Stanners does show a significant increase in depth in the area which corresponds to the observed pattern and timing of flooding. This suggests that the model is accurately simulating the observed flooding situation. However, whether or not the processes underlying this simulation are accurate, cannot be validated with the available data.

4.3.2. Validation of flood timeline

The success of the model at simulating the timings of the December 2015 flood was assessed based on the 15 min resolution time-series animations produced by the model. Table 4 shows the simulated timeline against the observed timings and demonstrates that the model was successful at predicting the timings of pathways FP1-4 as it simulated the pathways in the observed order, and either at the correct time, or within the time-periods identified by participants. In simulating FP5, the model showed a significant increase in depth in these areas from 18.30 GMT onwards (Fig. 5) where it showed a 30 min offset from the observed time. However, it is also possible this offset reflected variation in the timing of the effect observed by participants rather than any error in the model itself.

4.3.3. Validation of flood impacts

Section 3 has already outlined the partial validation of the flood extents of the 5th December 2015 flood event, which demonstrated that the model achieved 90% global accuracy in simulating maximum flood extent and water levels. However, the simulation of local water levels (and hence flood depth) can also be assessed using quantitative data on flood levels derived from imagery obtained across the area of interest. Eighteen images were collected as part of the research that could be used for the validation. Of these, 12 were capable of being used for validation of flood impacts, with 4 located along the Dilston Haugh flood defence, two each at the Stanners and Station Road, and three at the Cricket Club (Fig. 5), providing coverage of the majority of the study area. Eight of these images provided information on the maximum flooded depth and could be used to quantify the variation in observed and simulated depths. Four images did not provide any direct information on maximum depths, but provided a minimum constraint to simulated maximum depths as they showed inundation depths on Sunday 6th December, on the waning limb of the flood hydrograph.

Table 5 shows that there was variable success in the simulation of local flood depths. Along the flood embankment at Dilston Haugh (Table 5, photographs 1–5), the model consistently underestimated flood depths overtopping the flood embankment by an average of

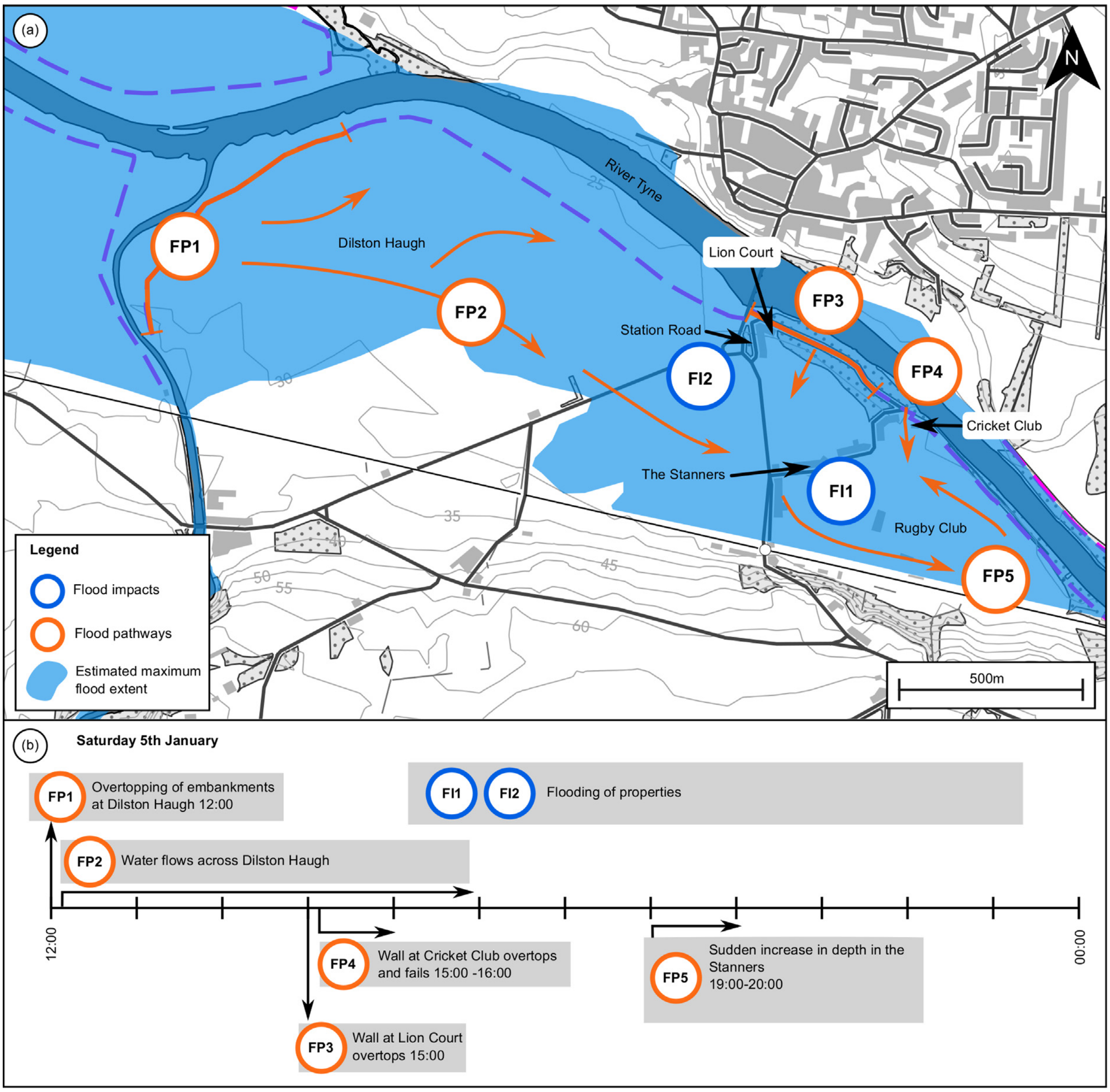


Fig. 4. Reconstruction of the (a) spatial distribution of flood pathways and impacts, and (b) timings, of the December 2015 flood using the VGI database. Pathways are referenced in order of occurrence. The reconstruction indicated three principle areas of overtopping, with two main pathways across the floodplain and two main areas of impact. The flood timings indicated that water began to overtop the Dilston Haugh defences at approximately 12:00 GMT on the 5th, with the overtopping of the Lion Court and Cricket Club defences occurring later. The sudden increase in flooding between 19:00 GMT and 20:00 GMT represented the backing up of flood waters from the Rugby Club as part of FP5.

0.25 m and up to a maximum of 0.50 m. At The Stanners and the Cricket Club (Table 5, photographs 8, 9 and 12) the model was more successful, with the difference between interpreted and simulated depths of only 0.02 m and 0.16 m respectively. For those images which provided only a minimum constraint to the simulated depths, the modelled depth exceeded the minimum constraint in all cases. These results suggest that there were disparities in the way that the model simulated the flow of water into and/or out of the study area. The underestimation of depths along the Dilston Haugh defences suggested that this pathway was not correctly simulated, with too little flood water overtopping the defences at this location. That local flood depths at The Stanners and the Cricket Club were more accurate suggesting that overtopping at this location might be too great. These results were substantiated by the maximum extent results (Fig. 3), which showed overtopping of the embankments at the Rugby Club, something not reported in the VGI database. Taken together, these results demonstrated that, at a local scale, simulation of inundation depths and extents was quite variable. This was despite the model showing high levels of accuracy at a global scale. These results likely reflect inaccuracies in the bare earth DEM which influenced simulated flow at a local scale. These inaccuracies could potentially have been introduced either during the pre-processing filtering process or during the resampling of the data from 2 m to 10 m resolution.

5. Discussion

This paper has introduced a new approach to flood model validation. The approach uses a VGI database collected during and immediately after a severe flood event to reconstruct and validate event dynamics. This approach builds on traditional, statistical approaches which are typically spatially or temporally limited and do not give a full picture of how an inundation model is performing at a local scale. The approach has been tested using a VGI database collected following a

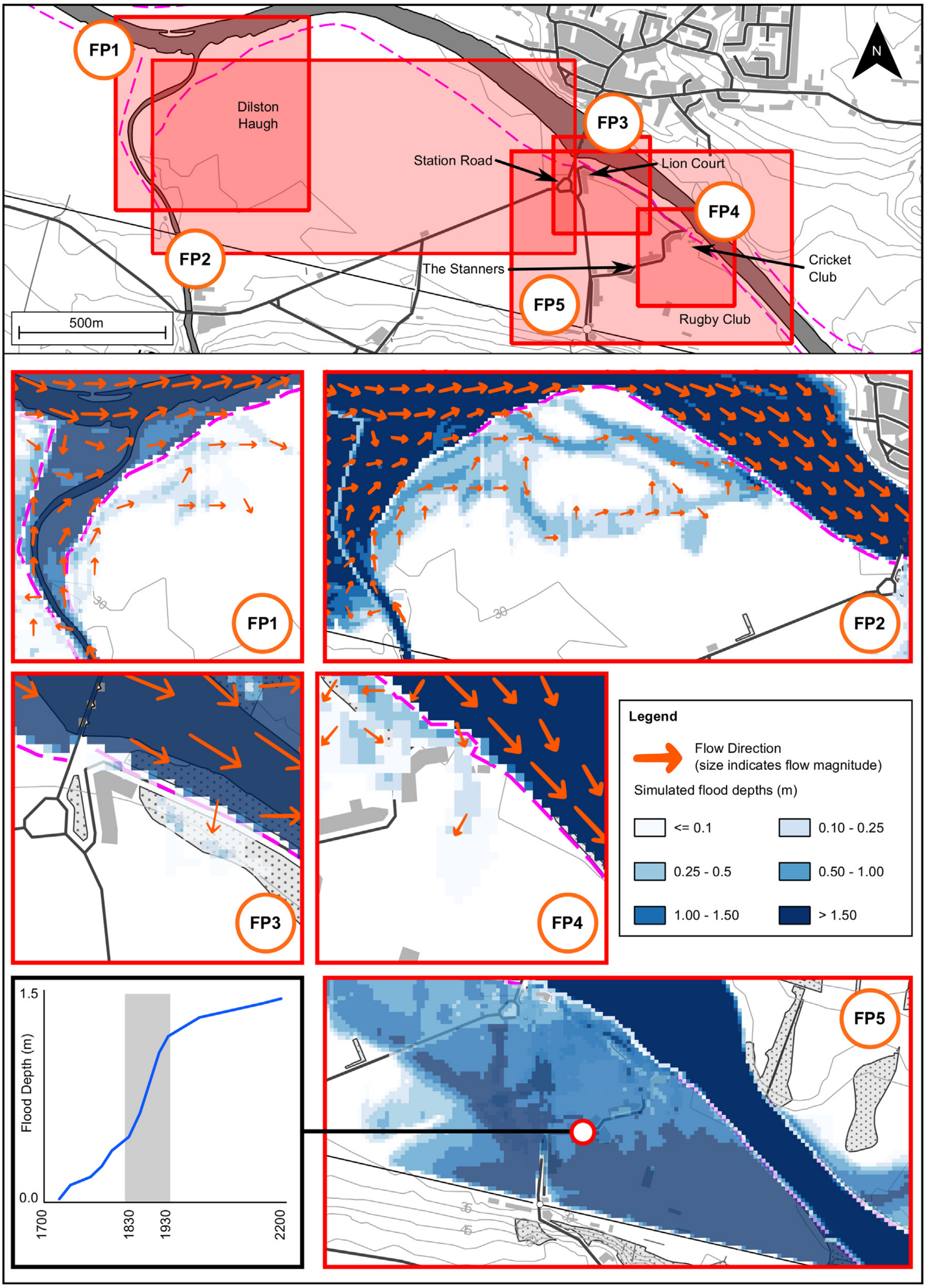


Fig. 5. Simulation results used for the validation of flood pathways. Validation was undertaken dynamically using GIS but for the purposes of static display results are extracted from the model for the time which corresponds with the flood pathway being demonstrated. FP5 shows flood depth change through time for the location on The Stanners indicated in the inset map and the graph highlights the rapid increase in depth shown by the simulation between 18.30 GMT and 19.30 GMT, corresponding with the conditions reported by research participants.

Table 4
Results of the validation of Flood Timings showing that the model was, in the majority of cases, able to accurately simulate both the relative order of events and also their specific times reported by participants.

Pathway	Observed time (GMT)	Simulated time (GMT)
FP1	12:00	12:00
FP2	12:00 onwards	12:00 onwards
FP3	15:00 – 16:00	15:30
FP4	16:00 – 17:00	16:30
FP5	19:00 onwards	18.30 onwards

severe flood which occurred at Corbridge, UK in December 2015.

5.1. Evaluating the success of the experimental validation method

The results of the research demonstrate that the experimental approach offers a more comprehensive validation of event dynamics than offered by traditional statistical approaches. At a global scale, established quantitative validation methods were used to assess the goodness-of-fit between simulated and observed water levels at river gauges, and between observed and simulated maximum flooded extents. The simulation shows RMSE values of < 0.5 and NSE values of > 0.9 at all available gauges, and a 90% accuracy in simulating the observed maximum extents. This is equal to or better than other similar modelling studies using LiSFLOOD-FP (Renschler and Wang, 2017; Wing et al., 2017), and suggests that the model is successfully simulating the inundation seen during the December 2015 flood event.

However, these established metrics only provide an incomplete, spatially and temporally limited, validation of the model performance (Hunter et al., 2007). The results of the experimental method outlined indicate that the more comprehensive validation is able to identify areas of model under-performance not identified by established global statistical approaches. In particular, the experimental validation shows that, although the model accurately simulates the timeline and locations of flood pathways, it incorrectly simulates the processes of overtopping and consequently local inundation depths. These results likely reflect localised inaccuracies in the underlying 10 m resolution DEM used for the model or the need for greater spatial variability in the parameterisation of roughness, both which could influence the flow of water across the floodplain which is not identified at a global scale. This would have potentially serious consequences if the model was to be used for local emergency response planning, or informing, for example, population evacuation strategies (Simonovic and Ahmad, 2005).

5.2. VGI data as an alternative to ‘established’ data sources

Fig. 6 categorises the data used in the study according to its

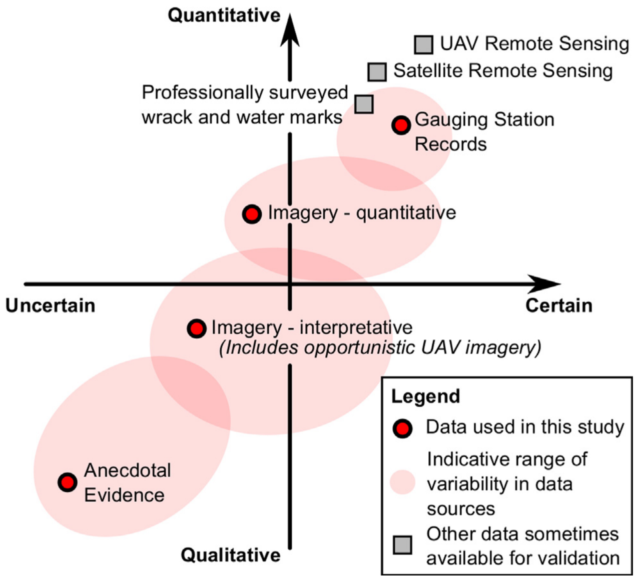


Fig. 6. Categorisation of the VGI datasets collected and used in this study in comparison to established datasets used for model validation. Quantitative imagery are those imagery from which direct quantitative measurements can be made (e.g. wrack marks), whilst interpretative imagery provide non-quantitative indicators (e.g. flow pathways), including opportunistically collected UAV survey data.

qualitative-quantitative nature and its degree of certainty, in comparison to more established data sources. Fig. 6 shows how the VGI data is set apart from traditional data in its range of sources and how it comprises a blend of quantitative, semi-quantitative, and qualitative data. The study demonstrates that this range of data sources makes it possible to understand and reconstruct flood event dynamics using the VGI data as a standalone dataset. As shown through the validation of the flood timeline, and local scale pathways and impacts presented here, VGI data offers opportunities for validating aspects of the flood inundation models at spatial and temporal scales which would be almost impossible using traditional means. This makes VGI a valuable alternative to traditional data sources, not just for immediate post-disaster response and recovery (Haworth and Bruce, 2015), but also as a longer term source of data to inform scientific analysis (Granell and Ostermann, 2016). This range of data sources has also been shown to be important to achieving a valid VGI dataset, particularly where a mixture of qualitative-quantitative data prevents the application of statistical metrics. Previous studies using more single-format databases have highlighted data validity as a limitation of VGI data (e.g. Klonner et al., 2016). However, we have demonstrated the usefulness of adopting a

Table 5
Comparison of spot water levels obtained from photographs with simulated maximum water levels. Photographs representing maximum water levels allow direct comparison with simulated levels. Minimum constraints represent the minimum level of flooding that should be achieved by the simulation.

Number	Location – description	Image category	Interpreted depth (m)	Simulated depth (m)	Difference (m)
1	Dilston Haugh Flood Defence – extent of overtopping and depths above flood wall	Maximum level	0.4	0.325	−0.075
2		Maximum level	0.4	0.279	−0.121
3		Maximum level	0.5	0.210	−0.29
4		Maximum level	0.3	0.030	−0.27
5		Maximum level	0.5	0.001	−0.499
6	Station Road – flood waters remaining at Station Road roundabout on Sunday morning	Minimum constraint	0.4	0.826	0.426
7		Minimum constraint	0.4	0.995	0.595
8	The Stanners – maximum water level marks on property walls at property on The Stanners	Maximum level	1.0	1.019	0.019
9		Maximum level	1.0	1.019	0.019
10	Cricket Club – water ponding within Cricket Club on Sunday	Minimum constraint	1.0	1.594	0.594
11	Cricket Club – water mark on wall shows Sunday level	Minimum constraint	1.0	1.582	0.582
12	Cricket Club – water mark shows maximum depth at club house	Maximum level	1.2	1.362	0.162

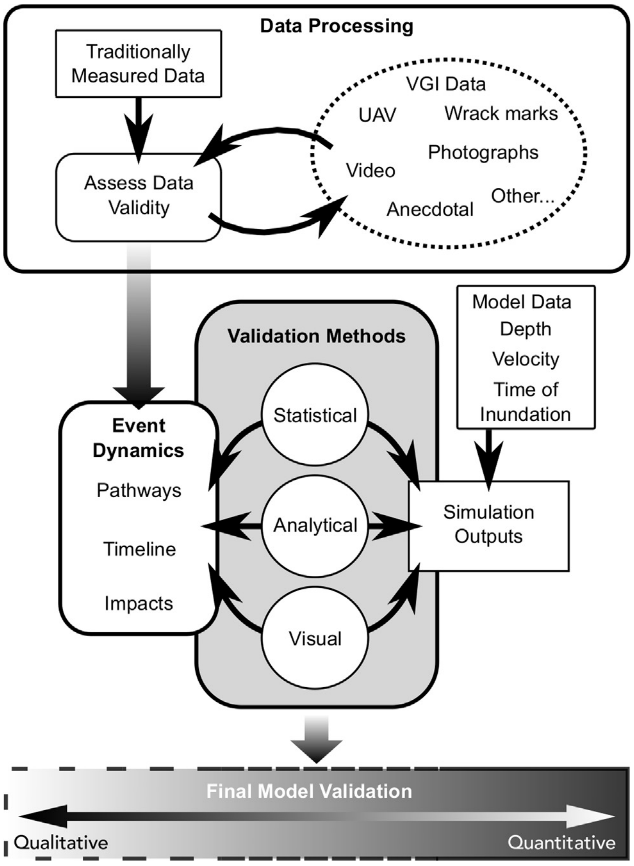


Fig. 7. A new framework for the validation of flood inundation models. The framework reflects the flexibility demonstrated in the study in using non-standard data sources to examine the underlying dynamics of flood events simulated by modern inundation models. The results of the validation reflects the diverse nature of the data and the validation methods which can be applied, and in so doing accepts a reduced quantified rigour in return for achieving a more comprehensive understanding of complex event dynamics.

much more flexible and interpretative model of data assessment based on triangulation with different data sources (Mays and Pope, 2000; Sousa, 2014; Wiggins and He, 2016).

5.3. A new framework for validating flood inundation models

This study has demonstrated a new approach to the validation of flood inundation models, with the aim being simulation of underlying event dynamics through better incorporation of VGI. The study has also demonstrated the usefulness of community-generated, VGI data as a primary input to the future validation of flood models. Building on these findings, we suggest a new framework for the validation of flood models (Fig. 7).

The proposed framework builds on current statistical approaches to validation by recognising the ability of current numerical models to simulate complex event dynamics, and the wider diversity of data which this study has shown to be applicable to model validation. The framework represents a three-stage process:

5.3.1. Data processing

The framework encourages a flexible and researcher-driven approach to assessing data validity which should reflect the data collected in its methods and outcome. As the fields of citizen science and VGI continue to evolve and mature, new practices of data collection and quality assessment will no doubt emerge (Granell and Ostermann, 2016; Hung et al., 2016). Greater standardisation through structures such as Citizen Observatories represent one way in which data collection might be expanded and improved (Lanfranchi et al., 2014; Wehn et al., 2015). Future improvements in personal technology will also likely make UAV data (Perks et al., 2016; Smith, 2015) and geo-located citizen data from personal electronic devices (Newman et al., 2012; Tang et al., 2017) more widely available. Taking these potential future developments into account, the framework aims to encourage the use of a wide range of data in many formats to allow cross referencing and triangulation between data sources.

5.3.2. Event dynamics

The framework proposes *pathways*, *timeline*, and *impacts* as broad categories through which principle event dynamics can be defined. This includes the traditionally assessed metrics of in-channel gauged levels and maximum inundation extents, but recognises that for many uses the parameterisation of numerical models in terms of these metrics alone is overly simplistic. By assessing a wider range of *processes* within the framework we can develop a more holistic validation and ensure that the dynamic simulation capabilities of modern numeric models are exploited to their full potential.

5.3.3. Validation methods

The framework adopts the same flexible approach to the validation of simulated dynamics as to data assessment. This recognises that different input data, simulations, and dynamics require different approaches to validation. Three broad types are proposed: *statistical*, incorporating established performance measures (Wing et al., 2017); *analytical*, reflecting semi-quantitative approaches such as the analysis of UAV footage and quantitative imagery demonstrated by this study; and *visual*, encompassing all techniques which rely on ‘on the face of it’ validation (Rykiel, 1996). The latter would include the assessment of pathways against the dynamic simulation outputs demonstrated in this study. The balance of validation techniques should reflect both the availability of simulation outputs and the availability of suitable data against which to validate them.

The final validation produced by the framework is a flexible one, influenced by the dynamics of the event, the data available, and methods adopted. The final result will likely lack the quantitative rigour of established statistical methods. Based on the results of this study we propose that some degree of inaccuracy and uncertainty can be accepted in return for the benefit of achieving a more comprehensive understanding of complex flood event dynamics (Granell and Ostermann, 2016). By adopting a more flexible approach to using VGI data in this way we can improve model validation, and, furthermore, open up the currently expert-led practices of flood risk assessment to greater public participation (Usón et al., 2016).

6. Conclusions

Numerical models are the foundation of flood risk assessment and management, used for understanding and mapping areas at risk from floods and planning management interventions. Recent improvements in computing power and model code, and increases in the availability of spatially distributed data on floodplain environments have increased the popularity of 2D models for providing detailed simulations of complex flood dynamics. However, improvements in model simulations have not been accompanied by corresponding improvements in model validation. Due to a lack of data from, during, and immediately after flooding events, validation of flood inundation models still grounded in the statistical assessment of spatially and temporally limited datasets, such as remotely-sensed flood extents or in-channel river gauging. The research presented in this study has demonstrated a new approach to the validation of flood inundation models, using VGI data to provide information on event dynamics not captured by traditionally measured datasets. In so doing, we have demonstrated that:

1. By collecting a wide range of VGI data from multiple sources it is possible to reconstruct in detail the dynamics of a severe flood. Although statistical validation is less rigorous, the quality of this reconstruction can be assessed through data triangulation and other qualitative approaches.
2. The reconstruction of flood pathways, timeline, and impacts of flooding can be used to validate the dynamic outputs of a 2D flood inundation model, and allow both spatial and temporal examination of model performance in simulating flooding processes.
3. The experimental model validation approach tested here enhances existing global statistical approaches to validation by examining the simulation of underlying flood processes using the case study of a large flood on the River Tyne, UK. The results of the test case indicate that a model assessed using traditional methods as having a global accuracy of over 90% in simulating gauged river levels and maximum flood extent does not accurately represent the actual pathways and impacts of the event. This is potentially highly significant when models are used in a dynamic way to plan and assess floodplain management interventions.

Drawing on these conclusions we propose a new, flexible framework for the validation of flood inundation models. In contrast to current approaches, the framework encourages the use of a diverse range of non-traditional data, now and into the future. Similarly, the framework encourages a mixture of approaches to validation to be adopted, leading to more flexibility depending on data availability and aspects of the simulation being considered. Although the final validation may lack the quantitative rigour of established global approaches, it provides a more comprehensive and bespoke examination of the model's performance, particularly for situations where dynamic model outputs are being used to inform potential floodplain interventions.

The results shown by this study also demonstrate the value of alternative data sources such as VGI, or data collected from citizen science programmes, to enhance and extend established data sources. We have demonstrated that many of the common criticisms of alternative data being 'messy' and unscientific can be understood or overcome by relatively simple procedures for quality control such as triangulation. However, data is, as demonstrated by other studies, not always as diverse or spatially distributed as that collected in this study, a fact that must be considered when translating this approach to other areas. For triangulation to be effective a mixture of overlapping data from different informants and from different sources (e.g. anecdotal, remote sensing, imagery) is essential. Additionally, all of these data need to be located, both spatially and temporally, within the study area or event of interest. This necessitates further research on the development of data collection approaches which combine the locally situated engagement adopted in this study with structured data collection approaches of citizen science or citizen observatories, and the spatial coverage of technology-based VGI approaches.

With predicted increases in the risk of flooding as a result of future climate change, numerical models are likely to continue to represent a significant asset in flood risk assessment practices. The VGI framework proposed here represents a more comprehensive process of model validation based on the more effective use of alternative data sources. This has the benefit of both allowing more comprehensive exploitation of modern numerical modelling to better simulate complex river-floodplain interactions and also encouraging the exploration and use of diverse datasets which may open up new perspectives on the use of numerical models for the creation flood risk knowledge. To effectively integrate the proposed validation framework into future modelling work, further research is urgently required in order to explore how technological VGI solutions could be developed to allow the routine collection of flood data through local engagement platforms such as citizen observatories.

7. Declarations of interest

None.

Acknowledgements

The authors would like to thank the members of the Corbridge Flood Action Group for their participation in this study. They would also like to thank the journal editors and two anonymous reviewers for their comments which helped shape and strengthen the final manuscript.

Funding

This work was supported by the Natural Environments Research Council [grant number NE/L002590/1]. Data presented in this manuscript can be obtained by contacting ER.

References

Altenau, E.H., Pavelsky, T.M., Bates, P.D., Neal, J.C., 2017. The effects of spatial resolution and dimensionality on modeling regional-scale hydraulics in a multichannel river. Water Resour. Res. 53, 1683–1701. http://dx.doi.org/10.1002/2016WR019396.

Barker, L., Hannaford, J., Parry, S., 2016. Briefing Note: Severity of the December 2015 floods – preliminary analysis [WWW Document]. Cent. Ecol. Hydrol http://www.ceh.ac.uk/news-and-media/blogs/briefing-note-severity-december-2015-floods-preliminary-analysis (accessed 11.15.16).

Baruch, A., May, A., Yu, D., 2016. The motivations, enablers and barriers for voluntary participation in an online crowdsourcing platform. Comput. Hum. Behav. 64, 923–931. http://dx.doi.org/10.1016/j.chb.2016.07.039.

Bates, P.D., De Roo, A.P.J., 2000. A simple raster-based model for flood inundation simulation. J. Hydrol. 236, 54–77. http://dx.doi.org/10.1016/S0022-1694(00)00278-X.

Bates, P.D., Horritt, M.S., Fewtrell, T.J., 2010. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. J. Hydrol. 387, 33–45. http://dx.doi.org/10.1016/j.jhydrol.2010.03.027.

Bradbrook, K.F., Lane, S.N., Waller, S.G., Bates, P.D., 2004. Two dimensional diffusion wave modelling of flood inundation using a simplified channel representation. Int. J. River Basin Manage. 2, 211–223. http://dx.doi.org/10.1080/15715124.2004.9635233.

Brandeis, M.-N.W., Carrera Zamanillo, M.I., 2017. Finding meaningful participation in volunteer geographic information and citizen science: a case comparison in environmental application. Cartogr. Geogr. Inf. Sci. 44, 539–550. http://dx.doi.org/10.1080/15230406.2016.1221779.

Charmaz, K., 2011. A Constructivist Grounded Theory Analysis of Losing and Regaining a Valued Self. In: Wertz, F.J. (Ed.), Five Ways of Doing Qualitative Analysis : Phenomenological Psychology, Grounded Theory, Discourse Analysis, Narrative Research, and Intuitive Inquiry. Guilford Press, New York, pp. 165–204.

Chow, V.T., 1959. Open-Channel Hydraulics. McGraw-Hill civil engineering series, McGraw-Hill, New York.

Clark, A., Emmel, N., 2008. Walking interviews: more than walking and talking. Presented at the "Peripatetic Practices": a workshop on walking, London.

Cobby, D.M., Mason, D.C., Horritt, M.S., Bates, P.D., 2003. Two-dimensional hydraulic flood modelling using a finite-element mesh decomposed according to vegetation and topographic features derived from airborne scanning laser altimetry. Hydrol. Process. 17, 1979–2000. http://dx.doi.org/10.1002/hyp.1201.

Coles, D., Yu, D., Wilby, R.L., Green, D., Herring, Z., 2017. Beyond "flood hotspots": Modelling emergency service accessibility during flooding in York. UK. J. Hydrol. 546, 419–436. http://dx.doi.org/10.1016/j.jhydrol.2016.12.013.

Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., Böhner, J., 2015. System for automated geoscientific analyses (SAGA) v. 2.1.4. Geosci. Model Dev. 8, 1991–2007. http://dx.doi.org/10.5194/gmd-8-1991-2015.

Cope, M., Elwood, S., 2009. Introduction: Qualitative GIS: Forging Mixed Methods through Representations, Analytical Innovations, and Conceptual Engagements. In: Cope, M., Elwood, S. (Eds.), Qualitative GIS: A Mixed Methods Approach. Sage, Thousand Oaks, CA, pp. 1–12.

Crower, R.A., 2009. Fluvial Design Guide Chapter 7 Hydraulic analysis and design.

Degrossi, L., De Albuquerque, J., Fava, M., Mendiondo, E., 2014. Flood Citizen Observatory: a crowdsourcing-based approach for flood risk management in Brazil.

Dowling, R., Lloyd, K., Suchet-Pearson, S., 2016. Qualitative methods 1: enriching the interview. Prog. Hum. Geogr. 40, 679–686. http://dx.doi.org/10.1177/0309132515596880.

Environment Agency, 2016. Impact Report Winter Flooding 2015-16 - Northumberland, Durham and Tees Area.

Evans, J., Jones, P., 2011. The walking interview: Methodology, mobility and place. Appl. Geogr. 31, 849–858. http://dx.doi.org/10.1016/j.apgeog.2010.09.005.

Fernández, A., Najafi, M.R., Durand, M., Mark, B.G., Moritz, M., Jung, H.C., Neal, J., Shastry, A., Laborde, S., Phang, S.C., Hamilton, I.M., Xiao, N., 2016. Testing the skill of numerical hydraulic modeling to simulate spatiotemporal flooding patterns in the

Logone floodplain. Cameroon J. Hydrol. 539, 265–280. http://dx.doi.org/10.1016/j.jhydrol.2016.05.026.
García-Pintado, J., Neal, J.C., Mason, D.C., Dance, S.L., Bates, P.D., 2013. Scheduling satellite-based SAR acquisition for sequential assimilation of water level observations into flood modelling. J. Hydrol. 495, 252–266. http://dx.doi.org/10.1016/j.jhydrol.2013.03.050.
Gobeyn, S., Van Wesemael, A., Neal, J., Lievens, H., Adams, K., De Vleeschouwer, N., Vernieuwe, H., Schumann, G.J.P., Di Baldassarre, G., Baets, B., Bates, P.D., Verhoest, N.E.C., 2017. Impact of the timing of a SAR image acquisition on the calibration of a flood inundation model. Adv. Water Resour. 100, 126–138. http://dx.doi.org/10.1016/j.advwatres.2016.12.005.
Goodchild, M.F., 2007. Citizens as sensors: the world of volunteered geography. GeoJ. 69, 211–221. http://dx.doi.org/10.1007/s10708-007-9111-y.
Goodchild, M.F., Glennon, J.A., 2010. Crowdsourcing geographic information for disaster response: a research frontier. Int. J. Digit. Earth 3, 231–241. http://dx.doi.org/10.1080/17538941003759255.
Granell, C., Ostermann, F.O., 2016. Beyond data collection: Objectives and methods of research using VGI and geo-social media for disaster management. Comput. Environ. Urban Syst. 59, 231–243. http://dx.doi.org/10.1016/j.compenvurbsys.2016.01.006.
Haklay, M., Antoniou, V., Basiouka, S., Soden, R., Mooney, P., 2014. Crowdsourced geographic information use in government (Report to GFDRR). World Bank, London.
Hardy, R.J., Bates, P.D., Anderson, M.G., 1999. The importance of spatial resolution in hydraulic models for floodplain environments. J. Hydrol. 216, 124–136. http://dx.doi.org/10.1016/S0022-1694(99)00002-5.
Haworth, B., Bruce, E., 2015. A Review of Volunteered Geographic Information for Disaster Management: a Review of VGI for Disaster Management. Geogr. Compass 9, 237–250. http://dx.doi.org/10.1111/gec3.12213.
Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nat. Clim. Change 3. http://dx.doi.org/10.1038/nclimate1911.
Horita, F.E.A., de Albuquerque, J.P., Degrossi, L.C., Mendiondo, E.M., Ueyama, J., 2015. Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks. Comput. Geosci. 80, 84–94. http://dx.doi.org/10.1016/j.cageo.2015.04.001.
Horritt, M., Bates, P.D., 2001. Effects of spatial resolution on a raster based model of flood flow. J. Hydrol. 253, 239–249. http://dx.doi.org/10.1016/S0022-1694(01)00490-5.
Hung, K.-C., Kalantari, M., Rajabifard, A., 2016. Methods for assessing the credibility of volunteered geographic information in flood response: A case study in Brisbane, Australia. Appl. Geogr. 68, 37–47. http://dx.doi.org/10.1016/j.apgeog.2016.01.005.
Hunter, N.M., Bates, P.D., Horritt, M.S., Wilson, M.D., 2007. Simple spatially-distributed models for predicting flood inundation: a review. Geomorphology 90, 208–225. http://dx.doi.org/10.1016/j.geomorph.2006.10.021.
Hunter, N.M., Horritt, M.S., Bates, P.D., Wilson, M.D., Werner, M.G.F., 2005. An adaptive time step solution for raster-based storage cell modelling of floodplain inundation. Adv. Water Resour. 28, 975–991. http://dx.doi.org/10.1016/j.advwatres.2005.03.007.
Jung, Y., Kim, D., Kim, D., Kim, M., Lee, S.O., 2014. Simplified flood inundation mapping based on flood elevation-discharge rating curves using satellite images in gauged watersheds. Water 6, 1280–1299. http://dx.doi.org/10.3390/w6051280.
Klonner, C., Marx, S., Usán, T., Porto de Albuquerque, J., Höfle, B., 2016. Volunteered geographic information in natural hazard analysis: a systematic literature review of current approaches with a focus on preparedness and mitigation. ISPRS Int. J. Geo-Inf. 5, 103. http://dx.doi.org/10.3390/ijgi5070103.
Knigge, L., Cope, M., 2006. Grounded visualization: integrating the analysis of qualitative and quantitative data through grounded theory and visualization. Environ. Plan. A 38, 2021–2037. http://dx.doi.org/10.1068/a37327.
Kusenbach, M., 2003. Street phenomenology: the Go-Along as ethnographic research tool. Ethnography 4, 455–485. http://dx.doi.org/10.1177/146613810343007.
Lane, S.N., Landström, C., Whatmore, S.J., 2011a. Imagining flood futures: risk assessment and management in practice. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 369, 1784–1806. http://dx.doi.org/10.1098/rsta.2010.0346.
Lane, S.N., Odoni, N., Landström, C., Whatmore, S.J., Ward, N., Bradley, S., 2011b. Doing flood risk science differently: an experiment in radical scientific method. Trans. Inst. Br. Geogr. 36, 15–36. http://dx.doi.org/10.1111/j.1475-5661.2010.00410.x.
Lanfranchi, V., Wrigley, S.N., Ireson, N., Ciravegna, F., Wehn, U., 2014. Citizens' Observatories for Situation Awareness in Flooding, in: Proceedings of the 11th International ISCRAM Conference. Pennsylvania.
Lee, M., Abbot, C., 2003. The usual suspects? public participation under the Aarhus convention. Mod. Law Rev. 66, 80–108. http://dx.doi.org/10.1111/1468-2230.6601004.
Marsh, T., Kirby, C., Muchan, K., Barker, L., Henderson, E., Hannaford, J., 2016. The winter floods of 2015/2016 in the UK – a review. Centre for Ecology and Hydrology, Wallingford.
Mays, N., Pope, C., 2000. Assessing quality in qualitative research. BMJ 320, 50–52. http://dx.doi.org/10.1136/bmj.320.7226.50.
McCallum, I., Liu, W., See, L., Mechler, R., Keating, A., Hochrainer-Stigler, S., Mochizuki, J., Fritz, S., Dugar, S., Arestegui, M., Szoenyi, M., Bayas, J.-C.L., Burek, P., French, A., Moorthy, I., 2016. Technologies to support community flood disaster risk reduction. Int. J. Disaster Risk Sci. 7, 198–204. http://dx.doi.org/10.1007/s13753-016-0086-5.
McDougall, K., 2012. An assessment of the contribution of volunteered geographic information during recent natural disasters. In: Rajabifard, A., Coleman, D. (Eds.), Spatially Enabling Government, Industry and Citizens: Research and Development Perspectives. GSDI Association Press, Needham, MA, United States, pp. 201–214.
Muller, C., Chapman, l., Johnston, L., Kidd, S., Illingworth, C., Foody, S., Overeem, G., Leigh, A., 2015. Crowdsourcing for climate and atmospheric sciences: current status and future potential. Int. J. Climatol. 35, 3185–3203. http://dx.doi.org/10.1002/joc.4210.
Munich Re, 2013. Floods dominate natural catastrophe statistics in first half of 2013 [WWW Document]. URL https://www.munichre.com/en/media-relations/publications/press-releases/2013/2013-07-09-press-release/index.html (accessed 10.28.17).
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — a discussion of principles. J. Hydrol. 10, 282–290. http://dx.doi.org/10.1016/0022-1694(70)90255-6.
National Research Council, 2008. Public Participation in Environmental Assessment and Decision Making. National Academies Press.
Neal, J., Schumann, G., Bates, P., 2012. A subgrid channel model for simulating river hydraulics and floodplain inundation over large and data sparse areas. Water Resour. Res. 48. http://dx.doi.org/10.1029/2012WR012514.
Neal, J., Schumann, G., Fewtrell, T., Budimir, M., Bates, P.D., Mason, D., 2011. Evaluating a new LISFLOOD-FP formulation with data from the summer 2007 floods in Tewkesbury, UK: Evaluating a new LISFLOOD-FP formulation. J. Flood Risk Manage. 4, 88–95. http://dx.doi.org/10.1111/j.1753-318X.2011.01093.x.
Neal, J.C., Bates, P.D., Fewtrell, T.J., Hunter, N.M., Wilson, M.D., Horritt, M.S., 2009. Distributed whole city water level measurements from the Carlisle 2005 urban flood event and comparison with hydraulic model simulations. J. Hydrol. 368, 42–55. http://dx.doi.org/10.1016/j.jhydrol.2009.01.026.
S. Néelz G. Pender 2013 Benchmarking the latest generation of 2D hydraulic modelling packages (No. SC120002) Environment Agency Bristol.
Nester, T., Komma, J., Blöschl, G., 2016. Real time flood forecasting in the Upper Danube basin. J. Hydrol. Hydromech. 64, 404–414. http://dx.doi.org/10.1515/johh-2016-0033.
Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., Crowston, K., 2012. The future of citizen science: emerging technologies and shifting paradigms. Front. Ecol. Environ. 10, 298–304. http://dx.doi.org/10.1890/110294.
Pappenberger, F., Beven, K., Frodsham, K., Romanowicz, R., Matgen, P., 2007a. Grasping the unavoidable subjectivity in calibration of flood inundation models: a vulnerability weighted approach. J. Hydrol. 333, 275–287. http://dx.doi.org/10.1016/j.jhydrol.2006.08.017.
Pappenberger, F., Frodsham, K., Beven, K., Romanowicz, R., Matgen, P., 2007b. Fuzzy set approach to calibrating distributed flood inundation models using remote sensing observations. Hydrol. Earth Syst. Sci. 11, 739–752. http://dx.doi.org/10.5194/hess-11-739-2007.
Parkes, B.L., Cloke, H.L., Pappenberger, F., Neal, J., Demeritt, D., 2013. Reducing inconsistencies in point observations of maximum flood inundation level. Earth Interact. 17, 1–27. http://dx.doi.org/10.1175/2012EI000475.1.
Perks, M.T., Russell, A.J., Large, A.R.G., 2016. Technical note: advances in flash flood monitoring using unmanned aerial vehicles (UAVs). Hydrol. Earth Syst. Sci. 20, 4005–4015. http://dx.doi.org/10.5194/hess-20-4005-2016.
Refsgaard, J.C., Henriksen, H.J., 2004. Modelling guidelines—terminology and guiding principles. Adv. Water Resour. 27, 71–82. http://dx.doi.org/10.1016/j.advwatres.2003.08.006.
Renschler, C.S., Wang, Z., 2017. Multi-source data fusion and modeling to assess and communicate complex flood dynamics to support decision-making for downstream areas of dams: the 2011 hurricane irene and schoharie creek floods, NY. Int. J. Appl. Earth Obs. Geoinformation 62, 157–173. http://dx.doi.org/10.1016/j.jag.2017.06.002.
Reynard, N.S., Kay, A.L., Anderson, M., Donovan, B., Duckworth, C., 2017. The evolution of climate change guidance for fluvial flood risk management in England. Prog. Phys. Geogr. 41, 222–237. http://dx.doi.org/10.1177/0309133317702566.
Rollason, E., Bracken, L.J., Hardy, R.J., Large, A.R.G., 2018. Rethinking flood risk communication. Nat. Hazards 1–22. http://dx.doi.org/10.1007/s11069-018-3273-4.
Ruiz-Mallén, I., Riboli-Sasco, L., Ribrault, C., Heras, M., Laguna, D., Perié, L., 2016. Citizen Science: Toward Transformative Learning. Sci. Commun. 38, 523–534. http://dx.doi.org/10.1177/1075547016642241.
Rykiel, E.J., 1996. Testing ecological models: the meaning of validation. Ecol. Model. 90, 229–244. http://dx.doi.org/10.1016/0304-3800(95)00152-2.
Sampson, C.C., Fewtrell, T.J., Duncan, A., Shaad, K., Horritt, M.S., Bates, P.D., 2012. Use of terrestrial laser scanning data to drive decimetric resolution urban inundation models. Adv. Water Resour. 41, 1–17. http://dx.doi.org/10.1016/j.advwatres.2012.02.010.
Sampson, C.C., Smith, A.M., Bates, P.D., Neal, J.C., Alfieri, L., Freer, J.E., 2015. A high-resolution global flood hazard model. Water Resour. Res. 51, 7358–7381. http://dx.doi.org/10.1002/2015WR016954.
Savage, J.T.S., Bates, P.D., Freer, J.E., Neal, J.C., Aronica, G.T., 2016. When does spatial resolution become spurious in probabilistic flood inundation predictions? Hydrol. Process. 30, 2014–2032. http://dx.doi.org/10.1002/hyp.10749.
Schnebele, E., Cervone, G., 2013. Improving remote sensing flood assessment using volunteered geographical data. Nat Hazards Earth Syst Sci 13, 669–677. http://dx.doi.org/10.5194/nhess-13-669-2013.
Segura-Beltrán, F., Sanchis-Ibor, C., Morales-Hernández, M., González-Sanchis, M., Bussi, G., Ortiz, E., 2016. Using post-flood surveys and geomorphologic mapping to evaluate hydrological and hydraulic models: the flash flood of the Girona River (Spain) in 2007. J. Hydrol. 541, 310–329. http://dx.doi.org/10.1016/j.jhydrol.2016.04.039.
Simonovic, S.P., Ahmad, S., 2005. Computer-based Model for flood evacuation emergency planning. Nat. Hazards 34, 25–51. http://dx.doi.org/10.1007/s11069-004-0785-x.
Smith, K.W., 2015. Drone technology: benefits, risks, and legal considerations. Seattle J. EnvironLaw SJEL 5 [i]–302.
Smith, R.A.E., Bates, P.D., Hayes, C., 2012. Evaluation of a coastal flood inundation model using hard and soft data. Environ. Model. Softw. 30, 35–46. http://dx.doi.org/10.1016/j.envsoft.2011.11.008.
Sousa, D., 2014. Validation in qualitative research: general aspects and specificities of the

descriptive phenomenological method. Qual. Res. Psychol. 11, 211–227. http://dx.doi.org/10.1080/14780887.2013.853855.

Starkey, E., Parkin, G., Birkinshaw, S., Large, A., Quinn, P., Gibson, C., 2017. Demonstrating the value of community-based ("citizen science") observations for catchment modelling and characterisation. J. Hydrol. 548, 801–817. http://dx.doi.org/10.1016/j.jhydrol.2017.03.019.

Tang, Z., Zhou, Y., Yu, H., Gu, Y., Liu, T., 2017. Developing an interactive mobile volunteered geographic information platform to integrate environmental big data and citizen science in urban management. In: Seeing Cities Through Big Data. Springer Geography. Springer, Cham, pp. 65–81.

Teng, J., Jakeman, A.J., Vaze, J., Croke, B.F.W., Dutta, D., Kim, S., 2017. Flood inundation modelling: a review of methods, recent advances and uncertainty analysis. Environ. Model. Softw. 90, 201–216. http://dx.doi.org/10.1016/j.envsoft.2017.01.006.

Triglav-Cekada, M., Radovan, D., 2013. Using volunteered geographical information to map the November 2012 floods in Slovenia. Nat. Hazards Earth Syst. Sci. 13, 2753–2762. http://dx.doi.org/10.5194/nhess-13-2753-2013.

Usón, T.J., Klonner, C., Höfle, B., 2016. Using participatory geographic approaches for urban flood risk in Santiago de Chile: insights from a governance analysis. Environ. Sci. Policy 66, 62–72. http://dx.doi.org/10.1016/j.envsci.2016.08.002.

Wan, Z., Hong, Y., Khan, S., Gourley, J., Flamig, Z., Kirschbaum, D., Tang, G., 2014. A cloud-based global flood disaster community cyber-infrastructure: development and demonstration. Environ. Model. Softw. 58, 86–94. http://dx.doi.org/10.1016/j.envsoft.2014.04.007.

Wehn, U., Rusca, M., Evers, J., Lanfranchi, V., 2015. Participation in flood risk management and the potential of citizen observatories: a governance analysis. Environ. Sci. Policy 48, 225–236.

Wiggins, A., He, Y., 2016. Community-based Data Validation in Citizen Science. https://doi.org/10.13016/M2N733.

Wing, O.E.J., Bates, P.D., Sampson, C.C., Smith, A.M., Johnson, K.A., Erickson, T.A., 2017. Validation of a 30 m resolution flood hazard model of the conterminous United States. Water Resour. Res. http://dx.doi.org/10.1002/2017WR020917.

Wood, M., Hostache, R., Neal, J.C., Wagener, T., Giustarini, L., Chini, M., Corato, G., Matgen, P., Bates, P.D., 2016. Calibration of channel depth and friction parameters in the LISFLOOD-FP hydraulic model using medium-resolution SAR data and identifiability techniques. Hydrol. Earth Syst. Sci. 20, 4983–4997. http://dx.doi.org/10.5194/hess-20-4983-2016.

Journal of Hydrology 562 (2018) 267–280

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

The importance of volunteered geographic information for the validation of flood inundation models

E. Rollason[a,*], L.J. Bracken[a], R.J. Hardy[a], A.R.G. Large[b]

[a] Department of Geography, Durham University, Durham DH1 3LE, United Kingdom
[b] School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom

ARTICLE INFO

This manuscript was handled by G. Syme, Editor-in-Chief, with the assistance of Heather M. Smith, Associate Editor

Keywords:
Flooding
Hydraulic modelling
Model validation
Volunteered geographic information
Citizen science

ABSTRACT

Two dimensional flood inundation models capable of simulating complex spatially and temporally differentiated floodplain flows are routinely used to model and predict flooding. However, advances in modelling techniques have not been matched by improvements in model validation. Validation of flood models remains challenging due to a lack of available spatially-explicit data; traditionally measured data and validation approaches reveal little about the ability of a model to simulate the complex dynamics of floodplain flows, including the pathways, timeline, and impacts of an event. In this paper we propose a novel method for the validation of hydraulic models of flooding using quantitative and qualitative Volunteered Geographic Information (VGI). This method uses VGI data to enhance traditionally measured validation data by reconstructing the observed dynamics of a flood, allowing validation of the temporal and spatial simulation of these dynamics. We illustrate the method using a case study from Corbridge in the northeast of England, using VGI collected through participatory research with people affected by severe flooding in 2015. The results of the study demonstrate that VGI data can be used for the effective reconstruction of flood event dynamics. The results also reveal that the proposed validation approach is able to identify underperformance in the model's simulation of event dynamics not evaluated by standard global performance measures. Such a lack of evaluation can have adverse consequences where dynamic model outputs are used locally to influence floodplain management. As a result, we propose a new framework for model validation, adopting a pragmatic and flexible approach to examining event dynamics using a diverse range of data.

1. Introduction

Flooding is one of the most serious environmental hazards globally, with flooding the cause of almost 50% of all economic losses resulting from natural hazards (Munich Re, 2013); and losses are likely to increase under climate change as flooding is exacerbated (Hirabayashi et al., 2013; Reynard et al., 2017). The need to better understand current and future flood risks has led to a significant rise in the use of predictive numeric models to understand river processes, including flooding (Bates and De Roo, 2000; Hunter et al., 2007; Lane et al., 2011a; Parkes et al., 2013). The availability of high quality, spatially-distributed data on river environments (Cobby et al., 2003) means two dimensional models, capable of explicitly simulating complex, spatially and temporally-differentiated floodplain flows are now a standard approach in many fields, including the insurance industry (Bates and De Roo, 2000; Bradbrook et al., 2004; Hunter et al., 2007; Néelz and Pender, 2013; Teng et al., 2017). However, improvements in data, and advances in numerical modelling techniques, have not been matched by improvements in the validation of these models; the process by which we can assess whether our models agree with observations (Refsgaard and Henriksen, 2004). Established approaches to validation are typically spatially or temporally limited in scope by the availability of accurate datasets.

This paper seeks to address gaps in our existing data and practices of model validation. Using a case study from northeast England, we propose a new approach, which builds on existing statistical methods of comparison against observed data. We demonstrate that, by exploiting diverse, volunteered and crowd-sourced datasets, we can both spatially and temporally reconstruct the key dynamics of flood events. The approach demonstrates how alternative data-sources can be used to enhance existing data, providing information on flooding processes for which traditionally regarded data is rarely available. Finally, the approach offers a more holistic validation of the complex dynamics of floodplain flows, including the pathways, timeline, and impacts of events.

* Corresponding author at: Department of Geography, Science Laboratories, Durham University, South Rd, Durham DH1 3LE, United Kingdom.
E-mail address: e.d.rollason@durham.ac.uk (E. Rollason).

https://doi.org/10.1016/j.jhydrol.2018.05.002
Received 30 November 2017; Received in revised form 23 April 2018; Accepted 2 May 2018
Available online 04 May 2018

2. Application of volunteered geographic information in hazard assessment

2.1. VGI data in disaster risk reduction

Paucity of measured data on disasters, including floods, is common in the field of Disaster Risk Reduction (DRR). To address this issue, research has explored the use of non-standard, unscientific datasets derived from local communities within a disaster zone (Goodchild and Glennon, 2010). One data source being explored within DRR research is Volunteered Geographic Data (VGI: (Haklay et al., 2014)), defined as 'the widespread engagement of large numbers of private citizens, often with little in the way of formal qualifications, in the creation of geographic information' (Goodchild, 2007, p. 212). VGI datasets include any geo-located information on a disaster, and can comprise a diverse range of data including personal accounts, photographs and videos, and crowd-sourced measurements (Hung et al., 2016; McDougall, 2012; Triglav-Cekada and Radovan, 2013).

The use of VGI datasets has been demonstrated across a wide range of studies of hazard events (for systematic reviews of the current research base see Granell and Ostermann, 2016; and Klonner et al., 2016). For floods, the use of VGI data has been demonstrated across a range of applications. For instance, McCallum et al. (2016) utilised VGI to improve the availability of pre-event data on flood vulnerability in data-sparse regions, demonstrating how crowd-sourced information can enhance mapping for emergency responders after disasters. A number of studies have also explored the potential for collecting VGI datasets to inform real-time disaster response. For example, Wan et al. (2014) at a global scale, and Degrossi et al. (2014) and Horita et al. (2015), both working at city scale in Brazil, demonstrated cloud-based systems for the collection and processing of VGI flooding data. These systems synthesised diverse flooding datasets, providing real-time information for emergency response and developed a long-term database of information on historic floods. VGI has also been used in the post-event phase: Schnebele and Cervone (2013) and Triglav-Cekada and Radovan (2013) utilised VGI flooding imagery collected after the event to improve flood maps derived from satellite imagery. Such research demonstrates how the VGI data can provide spatially distributed information on even large flood events, and how it can also be used to validate remotely-sensed hazard maps at a local scale.

While these examples demonstrate the emerging, widespread application of VGI for disaster preparedness and response, they also demonstrate how limited and fragmented the use of VGI data is for many applications; reflecting the non-standard nature of the data. McCallum et al. (2016) use only participatory mapping for their vulnerability assessment, whilst Schnebele and Cervone (2013) and Triglav-Cekada and Radovan (2013) use only imagery for their flood mapping analysis. Wan et al. (2014), Degrossi et al. (2014), and Horita et al. (2015) collected a wider range of data, including citizen reports of flooding, but highlighted significant problems utilising such diverse datasets which cannot be automatically processed. Other criticisms of VGI datasets often focus on issues of data validity or the difficulties of assessing data quality in the absence of traditionally-measured data sources (Hung et al., 2016; Muller et al., 2015). As a result, many studies use collection of VGI data as an adjunct to traditional data, rather than as a source of data in its own right or as a standalone method for the creation of new knowledge about specific hazards such as flooding (Usón et al., 2016).

2.2. Emerging practices of engagement

In contrast to the VGI projects noted in Section 2.1, citizen science and citizen observatory programmes represent moves towards establishing new practices of geo-spatial knowledge co-creation. These efforts are driven by the need for greater public participation in environmental decision-making (National Research Council, 2008) laid out in the Aarhus Convention (Lee and Abbot, 2003) and the European Floods Directive (Wehn et al., 2015). Citizen science and citizen observatories have been demonstrated across a range of disciplines including flooding and hydrology (Lanfranchi et al., 2014; Muller et al., 2015; Ruiz-Mallén et al., 2016; Starkey et al., 2017), and research has begun to demonstrate how citizen-led, locally collected data can provide valuable information for enhancing our understanding of catchment processes and planning catchment interventions (Starkey et al., 2017). In contrast to the often *ad-hoc* collection of VGI data, citizen science typically involves engaged and trained participants and rigid data collection frameworks to help overcome issues of data validity (Wiggins and He, 2016).

However, an issues arises: flood events, in common with other disasters, represent situations in which data can often only be collected in an *ad-hoc* fashion, as the presence of local volunteers able and willing to collect data cannot be guaranteed (Starkey et al., 2017). This is particularly relevant as citizen science programmes are often limited to small numbers of participants (Baruch et al., 2016), meaning drop-outs during an event would have a greater impact on the data collected. Efforts therefore need to be made to understand how we can integrate the opportunities for large scale engagement represented by VGI with the opportunities for local participation, and the improvements in data quality, represented by citizen science. Studies have begun to explore how integrating citizens into activities beyond simple data collection can improve engagement and data quality, for example see Starkey et al. (2017), but in the context of flooding this field is still in its infancy. However, there is obvious potential for a more integrated approach between large scale VGI data collection and the more locally focused nature of citizen science (see Brandeis and Carrera Zamanillo, (2017) for further details).

2.3. Integrating citizen data into the validation of flood inundation models

One situation which potentially offers the opportunity to integrate citizen science and VGI in this way is in the construction and validation of numerical flood inundation models of flood-affected communities. Flood inundation modelling forms a cornerstone of flood risk assessment (Bates and De Roo, 2000; Hunter et al., 2007; Lane et al., 2011a; Parkes et al., 2013). It informs almost all flood management activities, from monitoring and warning systems (Nester et al., 2016), to evacuation planning (Simonovic and Ahmad, 2005) and emergency response (Coles et al., 2017), to the design and construction of future developments (Pappenberger et al., 2007a). However, at present, flood modelling is primarily an expert-led activity with little or no citizen involvement (Lane et al., 2011b).

The established approach to validating inundation model outputs is to match available historical data to simulated outputs (Pappenberger et al., 2007a). The goodness-of-fit between predicted and observed river levels can be assessed using statistical best-fit techniques such as Nash-Sutcliffe Model Efficiency (NSME) (Nash and Sutcliffe, 1970) or Root Mean Square Error (RMSE) (Altenau et al., 2017). Similarly, point-in-time global flood extents can also be assessed using binary performance measures such as the Critical Success Index (C), which compares the extent of simulated inundation to the observed inundation (Wing et al., 2017). What tests are undertaken is dependent upon data availability. In-channel river level data is a source of historical information commonly available in medium and large catchments (Hunter et al., 2007; Parkes et al., 2013). To examine out of bank inundation, high resolution aerial and satellite imagery (Renschler and Wang, 2017), multiband remote sensing such as LANDSAT (Fernández et al., 2016; Jung et al., 2014), or other sensors such as Synthetic Aperture Radar (García-Pintado et al., 2013; Pappenberger et al., 2007b; Wood et al., 2016) can all be used. Studies have also demonstrated the usefulness of ground observations of wrack and water marks in reconstructing maximum inundation extents and levels, (Neal et al., 2009; Parkes et al., 2013; Segura-Beltrán et al., 2016). However, collection of this latter form of flood inundation evidence typically requires post-event surveys which are time and resource consuming and often yield spatially limited results (Segura-Beltrán et al., 2016).

The validation of model outputs is therefore constrained by data availability to being either spatially or temporally limited: gauged river levels may record levels throughout an event but are limited to discrete locations; whilst remote sensing can provide spatially extensive information on inundation but only at discrete time points. Consequently, established statistical techniques for model validation have been unable to assess the effectiveness of models in simulating both spatial **and** temporal event dynamics (Hunter et al., 2007). These dynamics include the pathways which water takes across the floodplain, the flood timeline, and local variation in flood impacts; all of which are capable of being simulated in detail by current 2D inundation models (Teng et al., 2017). This disparity between the complexity of current inundation models and the relative lack of data against which to test them represents an opportunity to integrate citizen-collected data into existing, expert-led practices of knowledge creation. Thus far however, there has been little exploration of this issue.

3. Methods

In this research we build on the methodology used by Smith et al. (2012) by demonstrating how VGI data should be used more routinely for model validation as a dataset in its own right. Smith et al. (2012) provide a demonstration of the use of a diverse VGI database to construct and validate a model of coastal flood defence overtopping. They utilise VGI to build the model, by using locally recorded locations of flood defence overtopping as point inflows into the model domain. They also validate its outputs, reconstructing the observed flood extents and depths at properties using historical photographs and media accounts. However, the approach demonstrated was limited by the data used, which was confined to imagery and records of depth at specific locations. By examining only modelled extent and depth, the method provides a spatial but not a temporal validation. The resultant model cannot examine the functioning of the model in simulating flood dynamics in more detail, nor does the study explore how VGI could be used more comprehensively. This is reflected in Smith et al.'s conclusion that the data used represented "*useful* ***corroborating*** *evidence for the performance of the model*" (p. 43), after a more traditional validation using available measured data.

In this study we develop an experimental validation methodology which uses a wide range of data potentially available through VGI and participatory research approaches to examine different aspects of a simulation output. To demonstrate the method we use a database of VGI to reconstruct in detail a severe flood in the northeast of England, and use a VGI-based flood reconstruction to validate the outputs of a 2D flood inundation model of the event. Finally, we compare the outputs to more established methods of validation to demonstrate the success of the method.

3.1. Model build

We utilised the flood inundation model LISFLOOD-FP to produce simulated flood event outputs for our case study. LiSFLOOD-FP is a 2D finite difference model developed specifically to utilise high resolution topographic data to simulate floodplain dynamics (Bates et al., 2010; Hunter et al., 2005; Neal et al., 2012, 2011; Bates and De Roo, 2000). Although we used LISFLOOD-FP here, the validation approach developed should be considered generic, and is designed to be applicable to any 2D model that predicts dynamic floodplain inundation. The principle data requirements for the model are outlined in Table 1.

3.1.1. The case study: The 2015 Corbridge flood

The test case used in this study is the market town of Corbridge, located in the Tyne Valley in the northeast of England (Fig. 1). Corbridge was chosen to develop and test the experimental validation because of its recent history of severe flooding and the way its population were already engaged with ongoing flood research (Rollason et al., 2018).

Corbridge experienced extensive flooding when Storm Desmond resulted in record rainfall across areas of the north of England (Barker et al., 2016) on 5th December 2015. The flood, an event with a return period estimated to be between 100 and 200 years (Marsh et al., 2016), overtopped the flood defences at Corbridge, and inundated 70 properties on the south side of the River Tyne (Environment Agency, 2016).

Using LiSFLOOD-FP a model of the River Tyne was constructed, extending for approximately 30 km, with Corbridge situated approximately half way down the modelled reach. Fig. 1 shows the modelled reach and the main data used are discussed in Table 1. To predict the December 2015 flood event, the model was run for a 72 h period starting at 12:00 on Friday 4th December continuing until 12:00 on Monday 7th December. This period covered both the rising and falling limbs of the main hydrograph at Corbridge. Simulation results were generated for every 15 min period, predicting flood depths, flood velocity, and time of inundation.

3.2. Validating the model outputs using established approaches

Initial verification and calibration of the model was undertaken during the model build. The mesh resolution independence of the model was verified by testing against DEM resolutions of 5.0, 7.5, 10.0, and 20.0 m (Hardy et al., 1999; Horritt and Bates, 2001). The model was further calibrated against floodplain friction values, which were estimated from Chow (1959) based on satellite imagery and field visits. Differential friction values were applied to the channel of the Tyne and the main floodplain, with the area of the channel delineated based on satellite imagery. Manning's values for floodplain friction between 0.02 and 0.06 ($m^{1/3}\,s^{-1}$) and channel friction values between 0.03 and 0.07 ($m^{1/3}\,s^{-1}$) were used in the model calibration runs, validation of which was undertaken using established statistical approaches. Validation was also undertaken on the calibrated model as a baseline against which to test the effectiveness of the experimental methodology.

Two datasets were available for the validation using established statistical techniques: gauged river levels and observed flood extents for the estimated maximum extent. Gauged river levels were validated using both Nash-Sutcliffe Model Efficiency (NSME) and Root Mean Square Error (RMSE) (Altenau et al., 2017). Maximum flood extents were validated using the Critical Success Index (C) (Wing et al., 2017; Wood et al., 2016), sometimes referred to as the 'fit statistic' (Sampson et al., 2015). C tests the proportion of wet observed data that is replicated by the model on a per-pixel basis, accounting for both over- and under-prediction:

$$C = \frac{M_1O_1}{M_1O_1 + M_0O_1 + M_1O_0}$$

where M is the modelled outcome and O is the observed outcome, and 1 or 0 represents pixels that are either wet or dry. C can range from 0 (no match between simulated and observed inundation) to 1 (perfect match between simulated and observed inundation).

3.3. Developing a new solution for validating inundation models

3.3.1. The Volunteered Geographic information database

Participatory research in Corbridge was undertaken with the community at to develop a VGI database of local knowledge and experiences of the December 2015 flooding event. As part of wider participatory work being undertaken at Corbridge (see Rollason et al., 2018) we carried out two participatory mapping workshops with 10 research participants, and five individual walking interviews, after Evans and Jones (2011). Discussions and interviews were un- or semi-structured in nature (Dowling et al., 2016), with participants being encouraged to lead the discussion and discuss their own knowledge and experiences.

Table 1
The principle data requirements of the LiSFLOOD-FP model and the data used in the construction of a model for this study.

Model component	Data required	Data Used in the study
Topography	Pre-processed, 'bare-earth' raster grid of topography with buildings and vegetation removed	Environment Agency 2 m horizontal resolution 'bare earth' LiDAR data, resampled using averaging technique Structures, e.g. bridges and flood defences, added to the DEM prior to inclusion in the model
Inflow conditions	Stage or discharge inflows	Point inflows from Environment Agency gauging stations at 15 min temporal resolution
Outflow conditions	A downstream boundary derived from either gauged river levels or a free flow boundary	Free flow boundary using slope calculated from local DEM values
Floodplain friction parameters	A raster grid representing Manning's 'n' values for different landcover classes	Values estimated from Chow (1959) based on satellite imagery and field visits

During the mapping workshops participants were encouraged to locate their knowledge on blank maps of the study area, for example observed locations of defence overtopping or pathways of flood water flow. Walking interviews were also participant-led following either the natural go-along (Kusenbach, 2003), or participatory walking interview (Clark and Emmel, 2008) models. Spatial data were recorded either directly into GIS or onto paper maps for later digitisation. Verbal discussions were recorded and analysed by adopting a grounded theory approach (Charmaz, 2011), combining both the audio recording and visual representations (Knigge and Cope, 2006). Information provided in anecdotal accounts was triangulated with digital images and video taken during the event and collected during the participatory process.

The information were used to produce an extensive database of how the flood occurred (Table 2). Most of the data was collected from the local community but it was augmented by (non-georeferenced) footage from an unmanned aerial vehicle (UAV) identified on news footage immediately after the event, and collected by a local UAV enthusiast.

3.3.2. Using the VGI database to reconstruct the dynamics of a severe flood

During validation it is necessary to establish the main dynamics of the flooding event for which the model is being validated. To do this, we divided the VGI data into three information categories:

1. *Pathways* – data which provided information on the movement of flood water through the study area, including areas of overtopping and principle flow directions.
2. *Impacts* – data which provided information on the maximum extent of the flooding.

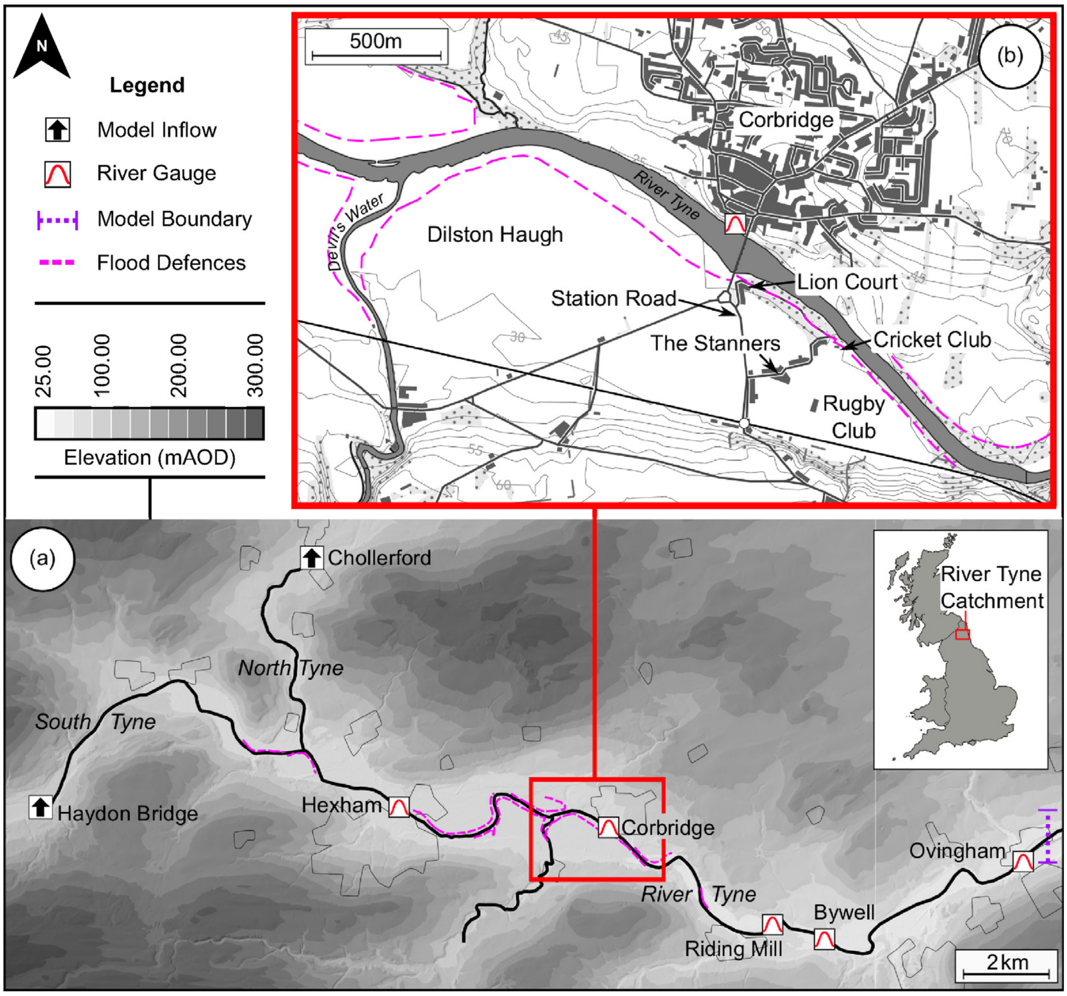


Fig. 1. (a) The modelled reach showing the key elements of the model and the locations of the boundary conditions used. (b) the Corbridge study area and locations referred to in the text.

Table 2
VGI data used for reconstruction of the December 2015 flood event. Data was collected between April and May 2016.

Data Type	Source	Quantity
Personal accounts	• Interviews and correspondence with individual members of the Corbridge Flood Action Group	5
Mapped data	• Group mapping workshops undertaken with members of the Corbridge Flood Action Group	Outputs from two group mapping workshops
Photographs	• Photographs taken during or immediately after the flooding event showing flood pathways or impacts, e.g. areas of gravel deposition or wrack lines, contributed by members of the Corbridge Flood Action Group	18
	• Photographs taken after the event by the researchers showing impacts e.g. wrack lines	
Video	• Videos taken during the flood event by members of the Corbridge Flood Action Group	2
	• Videos taken by UAV immediately after the flooding event and obtained through correspondence with research participants.	2 – one taken 24hrs after the peak of the flood and one 48hrs after the peak of the flood

3. *Timeline* – data which provided information on the timing of key events during the flood, including overtopping of defences, arrival of flood water at key locations, and inundation of properties.

Mapped data and personal accounts (anecdotal data) were combined into a single vector layer within a GIS, with the anecdotal data included within the layer as specific or linked attribute data following the qualitative GIS approaches of Cope and Elwood (2009). This layer was used to reconstruct a unified account of the event dynamics, including times of overtopping and inundation of properties. Photographs and videos were georeferenced and quantitative information was extracted where possible, for example the location of wrack or height of flood marks, or the direction of gravel deposition showing flow pathways. Where quantitative data was not collected directly, images were used simply for interpretation and to validate other data sources. Perks et al. (2016) have demonstrated how georeferenced UAV data can allow precise quantification of flood flows and flow vectors for an urban situation in Scotland. However, the UAV footage collected during the Corbridge study was obtained opportunistically and as a result did not contain the necessary metadata or ground control point information to allow it to be georeferenced. It was thus used in an analytical manner: using darker surface colours or isolated water bodies to indicate previous areas of inundation (Renschler and Wang, 2017). In areas where no footage was available, interpolation of the flood extent was undertaken based on expert judgement and using LiDAR topography.

3.3.3. *Quality control of VGI data*

The VGI dataset collected for this study is fragmentary and 'format-messy'. This makes the assessment of data quality using traditional quantitative measures difficult. However, it is still necessary to assess the extent to which we can have confidence in the data and the flood event reconstruction derived from it and, to do this, we adopted the approach of Mays and Pope (2000). This validation approach uses a researcher-led, reflexive approach relying on triangulation of different data sources to assess and validate individual pieces of information; for example the comparison of anecdotal accounts with imagery or physical evidence on the ground. This approach does not provide the quantifiable analysis of error normally required for model validation. Instead, the method identifies areas of error and uncertainty (spatial and temporal), or contested knowledge which can arise due to the nature of the VGI data being used.

3.3.4. *The experimental framework for model validation*

The experimental validation brought together the flood event reconstruction derived from the VGI database with the outputs of the LISFLOOD-FP model which represent the dynamics of the event. The outputs showed dynamic flood depths and flow vectors, times of inundation, and maximum flood extents.

Flood depths and times of inundation were extracted directly from the model at user-defined time-steps in raster grid format. As a velocity output, the model produces grids representing the flow of water between grid cells in both the x and y directions. To convert these velocity grids into flow vectors, the SAGA GIS tool 'Gradient Vectors from Directional Components' (Conrad et al., 2015) was used. An average across 4 grid cells (40 m) was used to reveal underlying flow directions which could be compared against the observed evidence. Fig. 2 shows the experimental approach and the VGI datasets used to validate the different dynamics of the event.

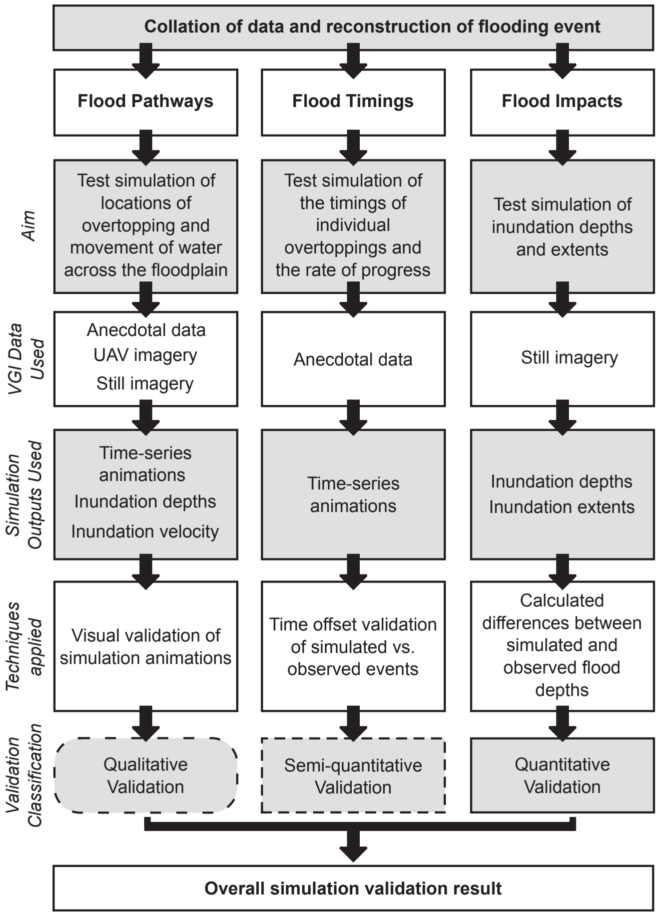


Fig. 2. The experimental approach showing the types of validation which can be applied, depending on the available information and how these correspond to the dynamics of the event. The availability of data and the validation methods adopted influences the nature of the final validation, which represents a blend of qualitative, semi-quantitative, and quantitative data and methods.

4. Results

4.1. *Calibration and validation of the model outputs using established methods*

Table 3 shows that the model performed consistently well in

Table 3
Results of the calibration and validation of the model using standard statistical techniques. Emboldened and highlighted rows indicate the best performing parameter sets which were used to estimate the parameters for the final model. The calibrated model used Manning's n of 0.03 ($m^{1/3}s^{-1}$) on the floodplain and 0.04 ($m^{1/3}s^{-1}$) in the channel, and a DEM resolution of 10 m.

Parameter Tested			RMSE				NSE (vs Gauge)				C%
			Hexham	Corbridge	Riding Mill	Bywell	Hexham	Corbridge	Riding Mill	Bywell	
	Channel	Floodplain									
Mannings '*n*'	0.02	0.03	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.04	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.05	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.06	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.02	0.07	0.519	0.823	0.818	0.725	0.774	0.773	0.744	0.851	76%
	0.03	0.03	0.235	0.407	0.370	0.247	0.953	0.944	0.948	0.983	90%
	0.03	0.04	0.354	0.590	0.501	0.385	0.895	0.884	0.904	0.958	89%
	0.03	0.05	0.354	0.590	0.501	0.385	0.895	0.884	0.904	0.958	89%
	0.03	0.06	0.332	0.538	0.456	0.338	0.907	0.903	0.920	0.968	89%
	0.03	0.07	0.319	0.508	0.430	0.312	0.915	0.914	0.929	0.972	89%
	0.04	**0.03**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	0.04	0.233	0.365	0.422	0.332	0.954	0.955	0.932	0.969	90%
	0.04	**0.05**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	**0.06**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.04	**0.07**	**0.259**	**0.444**	**0.334**	**0.191**	**0.944**	**0.934**	**0.957**	**0.990**	**90%**
	0.05	0.03	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
	0.05	0.04	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
	0.05	0.05	0.235	0.348	0.466	0.393	0.954	0.959	0.917	0.956	86%
	0.05	0.06	0.227	0.365	0.365	0.267	0.957	0.955	0.949	0.980	90%
	0.05	0.07	0.319	0.508	0.430	0.312	0.915	0.914	0.929	0.972	89%
	0.06	0.03	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
	0.06	0.04	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
	0.06	0.05	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
	0.06	0.06	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
	0.06	0.07	0.238	0.343	0.500	0.437	0.952	0.961	0.904	0.946	90%
DEM Resolution	5		0.093	0.436	1.271	0.761	0.993	0.936	0.381	0.836	88%
	7.5		0.220	0.435	0.341	0.710	0.959	0.937	0.956	0.857	88%
	10		**0.288**	**0.487**	**0.443**	**0.320**	**0.930**	**0.920**	**0.925**	**0.971**	**89%**
	20		**0.204**	**0.261**	**0.359**	**0.514**	**0.965**	**0.977**	**0.951**	**0.925**	**89%**
			RMSE				NSE				C%
			Hexham	Corbridge	Riding Mill	Bywell	Hexham	Corbridge	Riding Mill	Bywell	
Calibrated Model (Mannings '*n*' FP 0.03 Ch 0.04 / DEM resolution 10m)			0.259	0.443	0.335	0.194	0.944	0.934	0.957	0.989	90%

simulating gauged water levels along the whole modelled reach with a floodplain Manning's n of between 0.03 and 0.07 ($m^{1/3}\,s^{-1}$) and a DEM resolution of either 10 or 20 m. This DEM resolution is in line with the recommendations of the UK Environment Agency Fluvial Design Guide (Crower, 2009), which suggests model resolutions of 25 m in rural areas and 10 m for urban areas. It is also in line with other catchment or sub-regional studies, although there is significant variation in the resolutions used (Gobeyn et al., 2017; Neal et al., 2011; Renschler and Wang, 2017; Savage et al., 2016; Wing et al., 2017). Some studies have demonstrated the use of very high resolution topographic information, for example Sampson et al. (2012), but these are exclusively applied to small scale, urban studies rather than the larger, rural reaches such as that simulated in the current study.

Table 3 also indicates the goodness of fit, measured by the Critical Success Index C, between the simulated and observed maximum flood extents within the study area. The results indicate that all of the tested parameter sets achieved greater than 85% success in matching the observed peak flood extents. The calibrated model achieved a 90% success rate, which compares very favourably with other modelling studies which achieved between 50% and 90% success rates (Renschler and Wang, 2017; Wing et al., 2017). At a local scale, visual assessment of the simulated and observed extents (Fig. 3) show that within the area of interest there was considerable variability in areas of over- and underestimation. In particular, the model overestimated the extent of overtopping of the flood defences at Dilston Haugh (Fig. 3 location a) and at the Rugby Club (Fig. 3 location b), whilst it underestimated the extent of flooding on Dilston Haugh. It is considered likely that the bare earth DEM (vegetation and buildings removed) used in the model contained inaccuracies which influenced the flow of water across the floodplain, which will be discussed further below.

4.2. Application of the experimental validation approach

4.2.1. Reconstruction of the 2015 event dynamics

Fig. 4 shows the reconstruction of the dynamics of the December 2015 flood, undertaken using the VGI database. These can be divided into two types of dynamics: pathways of defence overtopping; and pathways of flow across the floodplain. The results indicated three pathways of defence overtopping (FP1, FP3, and FP4). FP1 and FP3 represented generalised overtopping of the defences (the extent of which is indicated on Fig. 4), whereas FP4 was identified as a specific location of overtopping at the junction between two defence types, which resulted in a distinct flow of water onto the Cricket Club from the north.

Two pathways of flow across the floodplain were also reconstructed. FP2 represented a general flow from the upstream areas of overtopping following the topography of the floodplain. FP5 represented backing up of water that was unable to return back to the river as a result of the flood defence and the high water levels in the river. This was manifested in the data as a reported sudden increase in depth at properties between 19:00 and 20:00 GMT on 5th December. Two main areas of impact were also represented at The Stanners (Fig. 4, FI1) and Station Road (Fig. 4, FI2). Although the distribution of properties affected by the flooding event was greater than that shown, no data was available

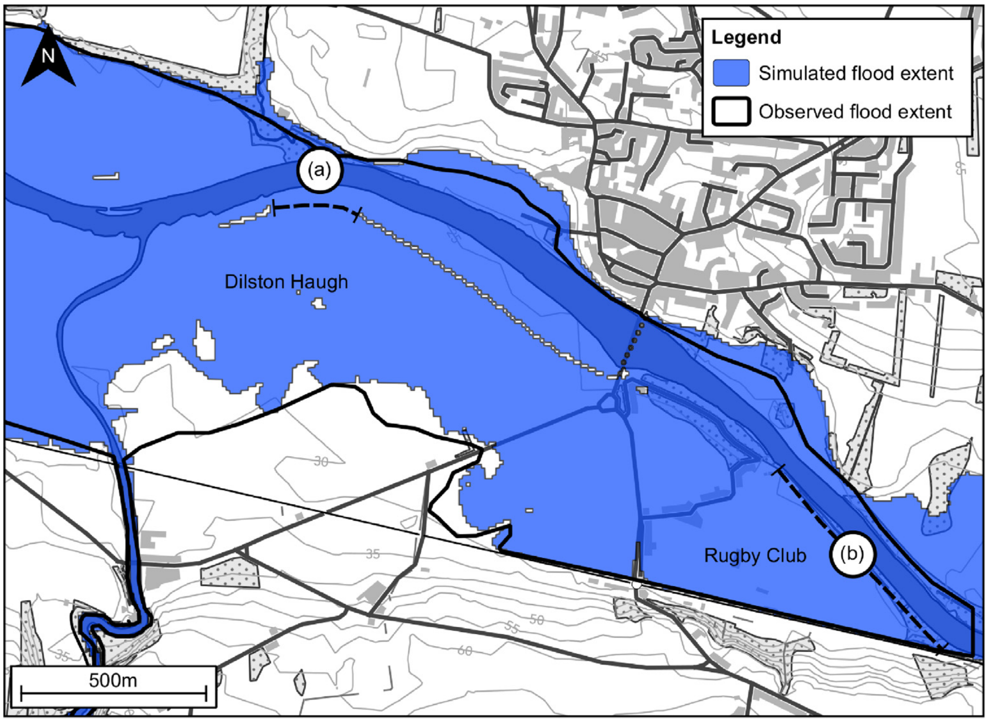


Fig. 3. The predicted maximum flood extent produced by the calibrated model compared to the observed maximum extent derived from analysis of the UAV imagery. The results show that there was some variability in the under- and over-prediction of flooding on both banks. In particular, locations (a) and (b) showed areas of overtopping of the defences which were not observed, indicating that the bare earth DEM used for the model may contain inaccuracies which affected the flow of water across the floodplain.

to validate the impacts in these other areas.

4.3. Results of the experimental validation

The calibrated model was validated against the key pathways, timings and impacts of the December 2015 flood identified in Section 4.2.

4.3.1. Validation of flood pathways

Pathways were identified from the model simulation using 15 min resolution time-series outputs of depth and velocity. Fig. 5 shows the results of the validation. The results indicate that the model was successful in simulating all of the major pathways identified in the observed data. In the case of FP1 and FP2 the model showed general overtopping of the defences along Dilston Haugh and flow following low-lying areas of the floodplain topography, which are potentially relict river channels. This is further north on the floodplain than was interpreted from the VGI, and is considered to reflect error within the VGI rather than in the model. This is because these flow pathways were not directly observed by the research participants; instead they were inferred from the direction of flood waters which entered their homes. For FP3 and FP4 the model showed successful differentiation between the two pathways. FP3 was simulated as overtopping of the wall at Lion Court, and there is also a distinct overtopping location at FP4. This results in flow across the Cricket Club from the north, reported by research participants, which is separate to the other flooding at and around Lion Court.

The processes behind the time-line of FP5 were the most contested within the VGI, with participants reporting a sudden increase in depth at The Stanners and Station Road (Fig. 5), but with considerable disagreement over the pathway this water had taken. Review of the flow vectors produced by the model for this area was not conclusive in identifying a simple backflow of water. However, calculation of the change in simulated inundation depth at The Stanners does show a significant increase in depth in the area which corresponds to the observed pattern and timing of flooding. This suggests that the model is accurately simulating the observed flooding situation. However, whether or not the processes underlying this simulation are accurate, cannot be validated with the available data.

4.3.2. Validation of flood timeline

The success of the model at simulating the timings of the December 2015 flood was assessed based on the 15 min resolution time-series animations produced by the model. Table 4 shows the simulated timeline against the observed timings and demonstrates that the model was successful at predicting the timings of pathways FP1-4 as it simulated the pathways in the observed order, and either at the correct time, or within the time-periods identified by participants. In simulating FP5, the model showed a significant increase in depth in these areas from 18.30 GMT onwards (Fig. 5) where it showed a 30 min offset from the observed time. However, it is also possible this offset reflected variation in the timing of the effect observed by participants rather than any error in the model itself.

4.3.3. Validation of flood impacts

Section 3 has already outlined the partial validation of the flood extents of the 5th December 2015 flood event, which demonstrated that the model achieved 90% global accuracy in simulating maximum flood extent and water levels. However, the simulation of local water levels (and hence flood depth) can also be assessed using quantitative data on flood levels derived from imagery obtained across the area of interest. Eighteen images were collected as part of the research that could be used for the validation. Of these, 12 were capable of being used for validation of flood impacts, with 4 located along the Dilston Haugh flood defence, two each at the Stanners and Station Road, and three at the Cricket Club (Fig. 5), providing coverage of the majority of the study area. Eight of these images provided information on the maximum flooded depth and could be used to quantify the variation in observed and simulated depths. Four images did not provide any direct information on maximum depths, but provided a minimum constraint to simulated maximum depths as they showed inundation depths on Sunday 6th December, on the waning limb of the flood hydrograph.

Table 5 shows that there was variable success in the simulation of local flood depths. Along the flood embankment at Dilston Haugh (Table 5, photographs 1–5), the model consistently underestimated flood depths overtopping the flood embankment by an average of

Journal of Hydrology 562 (2018) 267–280

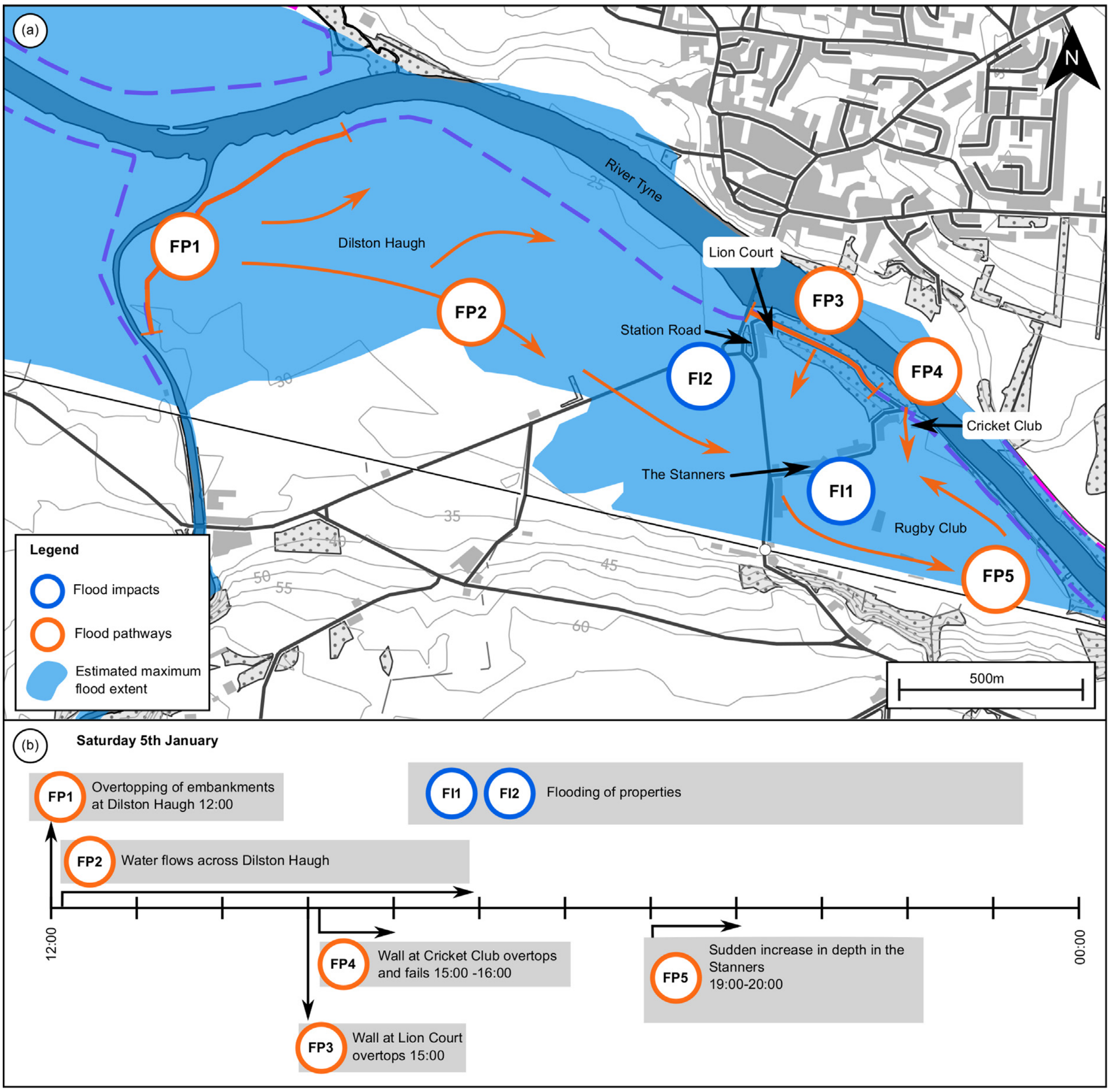


Fig. 4. Reconstruction of the (a) spatial distribution of flood pathways and impacts, and (b) timings, of the December 2015 flood using the VGI database. Pathways are referenced in order of occurrence. The reconstruction indicated three principle areas of overtopping, with two main pathways across the floodplain and two main areas of impact. The flood timings indicated that water began to overtop the Dilston Haugh defences at approximately 12:00 GMT on the 5th, with the overtopping of the Lion Court and Cricket Club defences occurring later. The sudden increase in flooding between 19:00 GMT and 20:00 GMT represented the backing up of flood waters from the Rugby Club as part of FP5.

0.25 m and up to a maximum of 0.50 m. At The Stanners and the Cricket Club (Table 5, photographs 8, 9 and 12) the model was more successful, with the difference between interpreted and simulated depths of only 0.02 m and 0.16 m respectively. For those images which provided only a minimum constraint to the simulated depths, the modelled depth exceeded the minimum constraint in all cases. These results suggest that there were disparities in the way that the model simulated the flow of water into and/or out of the study area. The underestimation of depths along the Dilston Haugh defences suggested that this pathway was not correctly simulated, with too little flood water overtopping the defences at this location. That local flood depths at The Stanners and the Cricket Club were more accurate suggesting that overtopping at this location might be too great. These results were substantiated by the maximum extent results (Fig. 3), which showed overtopping of the embankments at the Rugby Club, something not reported in the VGI database. Taken together, these results demonstrated that, at a local scale, simulation of inundation depths and extents was quite variable. This was despite the model showing high levels of accuracy at a global scale. These results likely reflect inaccuracies in the bare earth DEM which influenced simulated flow at a local scale. These inaccuracies could potentially have been introduced either during the pre-processing filtering process or during the resampling of the data from 2 m to 10 m resolution.

5. Discussion

This paper has introduced a new approach to flood model validation. The approach uses a VGI database collected during and immediately after a severe flood event to reconstruct and validate event dynamics. This approach builds on traditional, statistical approaches which are typically spatially or temporally limited and do not give a full picture of how an inundation model is performing at a local scale. The approach has been tested using a VGI database collected following a

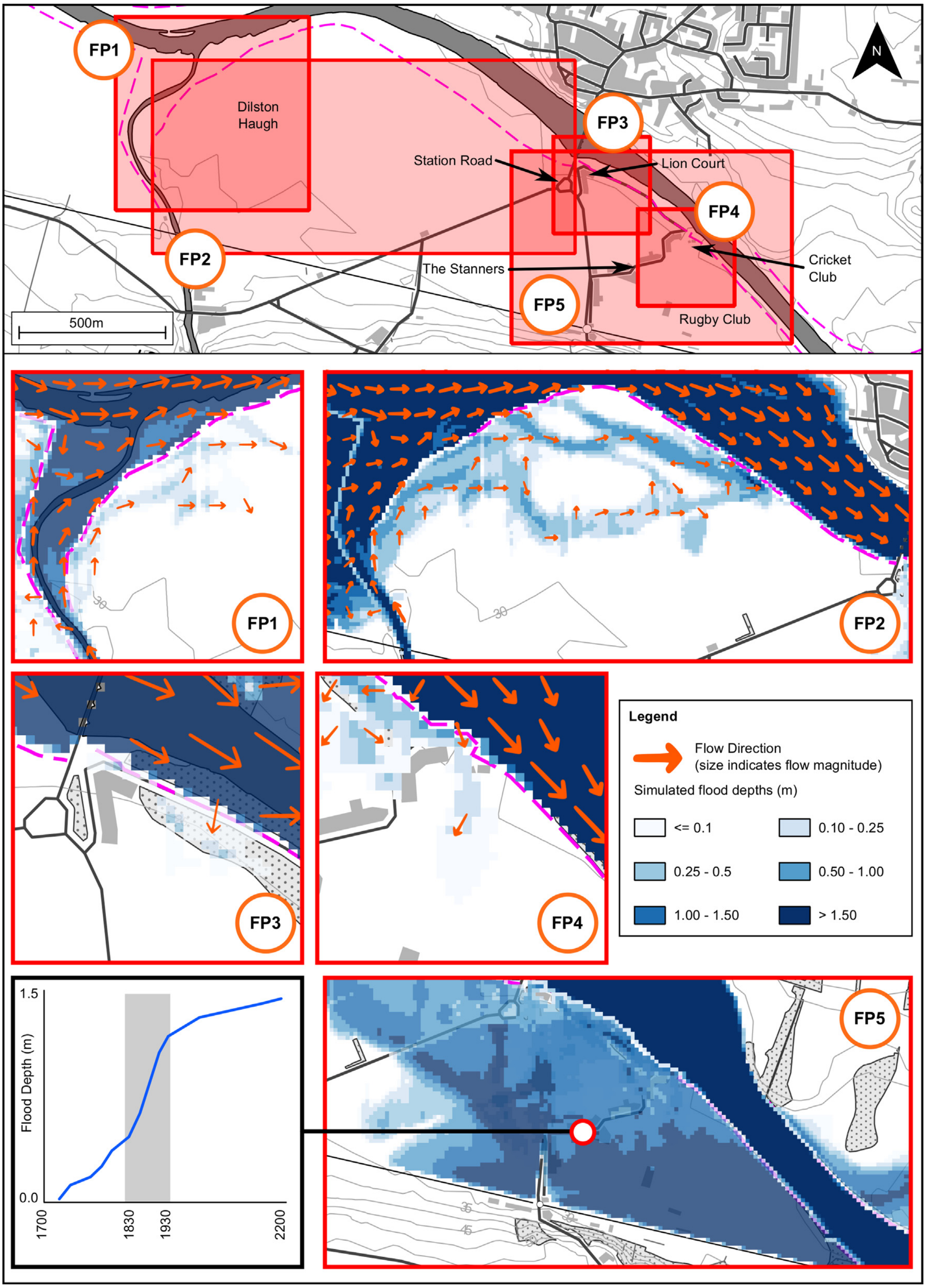


Fig. 5. Simulation results used for the validation of flood pathways. Validation was undertaken dynamically using GIS but for the purposes of static display results are extracted from the model for the time which corresponds with the flood pathway being demonstrated. FP5 shows flood depth change through time for the location on The Stanners indicated in the inset map and the graph highlights the rapid increase in depth shown by the simulation between 18.30 GMT and 19.30 GMT, corresponding with the conditions reported by research participants.

Table 4
Results of the validation of Flood Timings showing that the model was, in the majority of cases, able to accurately simulate both the relative order of events and also their specific times reported by participants.

Pathway	Observed time (GMT)	Simulated time (GMT)
FP1	12:00	12:00
FP2	12:00 onwards	12:00 onwards
FP3	15:00 – 16:00	15:30
FP4	16:00 – 17:00	16:30
FP5	19:00 onwards	18.30 onwards

severe flood which occurred at Corbridge, UK in December 2015.

5.1. Evaluating the success of the experimental validation method

The results of the research demonstrate that the experimental approach offers a more comprehensive validation of event dynamics than offered by traditional statistical approaches. At a global scale, established quantitative validation methods were used to assess the goodness-of-fit between simulated and observed water levels at river gauges, and between observed and simulated maximum flooded extents. The simulation shows RMSE values of < 0.5 and NSE values of > 0.9 at all available gauges, and a 90% accuracy in simulating the observed maximum extents. This is equal to or better than other similar modelling studies using LiSFLOOD-FP (Renschler and Wang, 2017; Wing et al., 2017), and suggests that the model is successfully simulating the inundation seen during the December 2015 flood event.

However, these established metrics only provide an incomplete, spatially and temporally limited, validation of the model performance (Hunter et al., 2007). The results of the experimental method outlined indicate that the more comprehensive validation is able to identify areas of model under-performance not identified by established global statistical approaches. In particular, the experimental validation shows that, although the model accurately simulates the timeline and locations of flood pathways, it incorrectly simulates the processes of overtopping and consequently local inundation depths. These results likely reflect localised inaccuracies in the underlying 10 m resolution DEM used for the model or the need for greater spatial variability in the parameterisation of roughness, both which could influence the flow of water across the floodplain which is not identified at a global scale. This would have potentially serious consequences if the model was to be used for local emergency response planning, or informing, for example, population evacuation strategies (Simonovic and Ahmad, 2005).

5.2. VGI data as an alternative to 'established' data sources

Fig. 6 categorises the data used in the study according to its qualitative-quantitative nature and its degree of certainty, in comparison to more established data sources. Fig. 6 shows how the VGI data is set apart from traditional data in its range of sources and how it comprises a blend of quantitative, semi-quantitative, and qualitative data. The study demonstrates that this range of data sources makes it possible to understand and reconstruct flood event dynamics using the VGI data as a standalone dataset. As shown through the validation of the flood timeline, and local scale pathways and impacts presented here, VGI data offers opportunities for validating aspects of the flood inundation models at spatial and temporal scales which would be almost impossible using traditional means. This makes VGI a valuable alternative to traditional data sources, not just for immediate post-disaster response and recovery (Haworth and Bruce, 2015), but also as a longer term source of data to inform scientific analysis (Granell and Ostermann, 2016). This range of data sources has also been shown to be important to achieving a valid VGI dataset, particularly where a mixture of qualitative-quantitative data prevents the application of statistical metrics. Previous studies using more single-format databases have highlighted data validity as a limitation of VGI data (e.g. Klonner et al., 2016). However, we have demonstrated the usefulness of adopting a

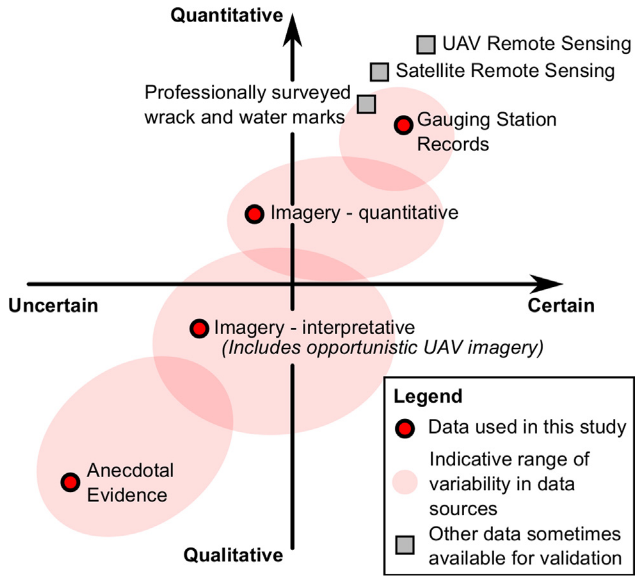


Fig. 6. Categorisation of the VGI datasets collected and used in this study in comparison to established datasets used for model validation. Quantitative imagery are those imagery from which direct quantitative measurements can be made (e.g. wrack marks), whilst interpretative imagery provide non-quantitative indicators (e.g. flow pathways), including opportunistically collected UAV survey data.

Table 5
Comparison of spot water levels obtained from photographs with simulated maximum water levels. Photographs representing maximum water levels allow direct comparison with simulated levels. Minimum constraints represent the minimum level of flooding that should be achieved by the simulation.

Number	Location – description	Image category	Interpreted depth (m)	Simulated depth (m)	Difference (m)
1	Dilston Haugh Flood Defence – extent of overtopping and depths above flood wall	Maximum level	0.4	0.325	−0.075
2		Maximum level	0.4	0.279	−0.121
3		Maximum level	0.5	0.210	−0.29
4		Maximum level	0.3	0.030	−0.27
5		Maximum level	0.5	0.001	−0.499
6	Station Road – flood waters remaining at Station Road roundabout on Sunday morning	Minimum constraint	0.4	0.826	0.426
7		Minimum constraint	0.4	0.995	0.595
8	The Stanners – maximum water level marks on property walls at property on The Stanners	Maximum level	1.0	1.019	0.019
9		Maximum level	1.0	1.019	0.019
10	Cricket Club – water ponding within Cricket Club on Sunday	Minimum constraint	1.0	1.594	0.594
11	Cricket Club – water mark on wall shows Sunday level	Minimum constraint	1.0	1.582	0.582
12	Cricket Club – water mark shows maximum depth at club house	Maximum level	1.2	1.362	0.162

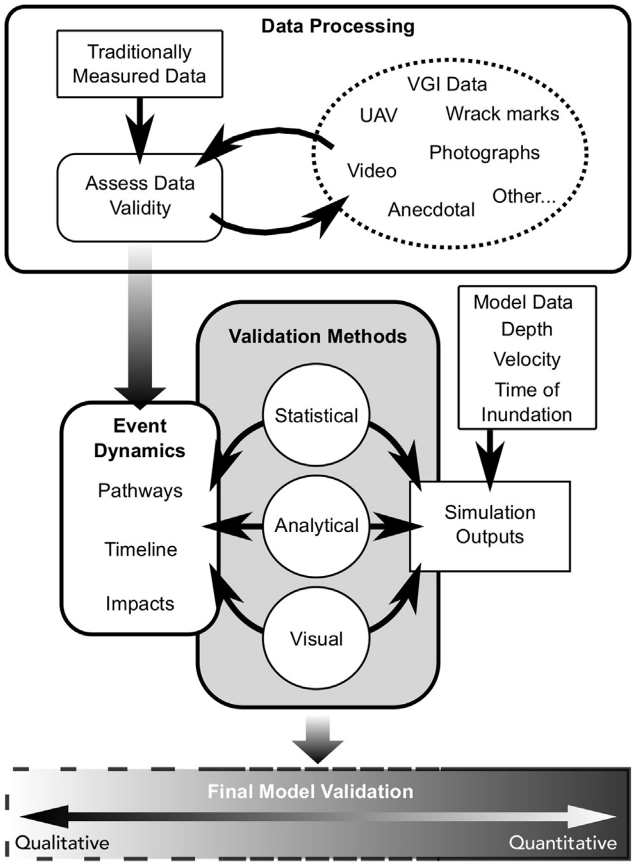


Fig. 7. A new framework for the validation of flood inundation models. The framework reflects the flexibility demonstrated in the study in using non-standard data sources to examine the underlying dynamics of flood events simulated by modern inundation models. The results of the validation reflects the diverse nature of the data and the validation methods which can be applied, and in so doing accepts a reduced quantified rigour in return for achieving a more comprehensive understanding of complex event dynamics.

much more flexible and interpretative model of data assessment based on triangulation with different data sources (Mays and Pope, 2000; Sousa, 2014; Wiggins and He, 2016).

5.3. A new framework for validating flood inundation models

This study has demonstrated a new approach to the validation of flood inundation models, with the aim being simulation of underlying event dynamics through better incorporation of VGI. The study has also demonstrated the usefulness of community-generated, VGI data as a primary input to the future validation of flood models. Building on these findings, we suggest a new framework for the validation of flood models (Fig. 7).

The proposed framework builds on current statistical approaches to validation by recognising the ability of current numerical models to simulate complex event dynamics, and the wider diversity of data which this study has shown to be applicable to model validation. The framework represents a three-stage process:

5.3.1. Data processing

The framework encourages a flexible and researcher-driven approach to assessing data validity which should reflect the data collected in its methods and outcome. As the fields of citizen science and VGI continue to evolve and mature, new practices of data collection and quality assessment will no doubt emerge (Granell and Ostermann, 2016; Hung et al., 2016). Greater standardisation through structures such as Citizen Observatories represent one way in which data collection might be expanded and improved (Lanfranchi et al., 2014; Wehn et al., 2015). Future improvements in personal technology will also likely make UAV data (Perks et al., 2016; Smith, 2015) and geo-located citizen data from personal electronic devices (Newman et al., 2012; Tang et al., 2017) more widely available. Taking these potential future developments into account, the framework aims to encourage the use of a wide range of data in many formats to allow cross referencing and triangulation between data sources.

5.3.2. Event dynamics

The framework proposes *pathways*, *timeline*, and *impacts* as broad categories through which principle event dynamics can be defined. This includes the traditionally assessed metrics of in-channel gauged levels and maximum inundation extents, but recognises that for many uses the parameterisation of numerical models in terms of these metrics alone is overly simplistic. By assessing a wider range of *processes* within the framework we can develop a more holistic validation and ensure that the dynamic simulation capabilities of modern numeric models are exploited to their full potential.

5.3.3. Validation methods

The framework adopts the same flexible approach to the validation of simulated dynamics as to data assessment. This recognises that different input data, simulations, and dynamics require different approaches to validation. Three broad types are proposed: *statistical*, incorporating established performance measures (Wing et al., 2017); *analytical*, reflecting semi-quantitative approaches such as the analysis of UAV footage and quantitative imagery demonstrated by this study; and *visual*, encompassing all techniques which rely on 'on the face of it' validation (Rykiel, 1996). The latter would include the assessment of pathways against the dynamic simulation outputs demonstrated in this study. The balance of validation techniques should reflect both the availability of simulation outputs and the availability of suitable data against which to validate them.

The final validation produced by the framework is a flexible one, influenced by the dynamics of the event, the data available, and methods adopted. The final result will likely lack the quantitative rigour of established statistical methods. Based on the results of this study we propose that some degree of inaccuracy and uncertainty can be accepted in return for the benefit of achieving a more comprehensive understanding of complex flood event dynamics (Granell and Ostermann, 2016). By adopting a more flexible approach to using VGI data in this way we can improve model validation, and, furthermore, open up the currently expert-led practices of flood risk assessment to greater public participation (Usón et al., 2016).

6. Conclusions

Numerical models are the foundation of flood risk assessment and management, used for understanding and mapping areas at risk from floods and planning management interventions. Recent improvements in computing power and model code, and increases in the availability of spatially distributed data on floodplain environments have increased the popularity of 2D models for providing detailed simulations of complex flood dynamics. However, improvements in model simulations have not been accompanied by corresponding improvements in model validation. Due to a lack of data from, during, and immediately after flooding events, validation of flood inundation models still grounded in the statistical assessment of spatially and temporally limited datasets, such as remotely-sensed flood extents or in-channel river gauging. The research presented in this study has demonstrated a new approach to the validation of flood inundation models, using VGI data to provide information on event dynamics not captured by traditionally measured datasets. In so doing, we have demonstrated that:

1. By collecting a wide range of VGI data from multiple sources it is possible to reconstruct in detail the dynamics of a severe flood. Although statistical validation is less rigorous, the quality of this reconstruction can be assessed through data triangulation and other qualitative approaches.
2. The reconstruction of flood pathways, timeline, and impacts of flooding can be used to validate the dynamic outputs of a 2D flood inundation model, and allow both spatial and temporal examination of model performance in simulating flooding processes.
3. The experimental model validation approach tested here enhances existing global statistical approaches to validation by examining the simulation of underlying flood processes using the case study of a large flood on the River Tyne, UK. The results of the test case indicate that a model assessed using traditional methods as having a global accuracy of over 90% in simulating gauged river levels and maximum flood extent does not accurately represent the actual pathways and impacts of the event. This is potentially highly significant when models are used in a dynamic way to plan and assess floodplain management interventions.

Drawing on these conclusions we propose a new, flexible framework for the validation of flood inundation models. In contrast to current approaches, the framework encourages the use of a diverse range of non-traditional data, now and into the future. Similarly, the framework encourages a mixture of approaches to validation to be adopted, leading to more flexibility depending on data availability and aspects of the simulation being considered. Although the final validation may lack the quantitative rigour of established global approaches, it provides a more comprehensive and bespoke examination of the model's performance, particularly for situations where dynamic model outputs are being used to inform potential floodplain interventions.

The results shown by this study also demonstrate the value of alternative data sources such as VGI, or data collected from citizen science programmes, to enhance and extend established data sources. We have demonstrated that many of the common criticisms of alternative data being 'messy' and unscientific can be understood or overcome by relatively simple procedures for quality control such as triangulation. However, data is, as demonstrated by other studies, not always as diverse or spatially distributed as that collected in this study, a fact that must be considered when translating this approach to other areas. For triangulation to be effective a mixture of overlapping data from different informants and from different sources (e.g. anecdotal, remote sensing, imagery) is essential. Additionally, all of these data need to be located, both spatially and temporally, within the study area or event of interest. This necessitates further research on the development of data collection approaches which combine the locally situated engagement adopted in this study with structured data collection approaches of citizen science or citizen observatories, and the spatial coverage of technology-based VGI approaches.

With predicted increases in the risk of flooding as a result of future climate change, numerical models are likely to continue to represent a significant asset in flood risk assessment practices. The VGI framework proposed here represents a more comprehensive process of model validation based on the more effective use of alternative data sources. This has the benefit of both allowing more comprehensive exploitation of modern numerical modelling to better simulate complex river-floodplain interactions and also encouraging the exploration and use of diverse datasets which may open up new perspectives on the use of numerical models for the creation flood risk knowledge. To effectively integrate the proposed validation framework into future modelling work, further research is urgently required in order to explore how technological VGI solutions could be developed to allow the routine collection of flood data through local engagement platforms such as citizen observatories.

7. Declarations of interest

None.

Acknowledgements

The authors would like to thank the members of the Corbridge Flood Action Group for their participation in this study. They would also like to thank the journal editors and two anonymous reviewers for their comments which helped shape and strengthen the final manuscript.

Funding

This work was supported by the Natural Environments Research Council [grant number NE/L002590/1]. Data presented in this manuscript can be obtained by contacting ER.

References

Altenau, E.H., Pavelsky, T.M., Bates, P.D., Neal, J.C., 2017. The effects of spatial resolution and dimensionality on modeling regional-scale hydraulics in a multichannel river. Water Resour. Res. 53, 1683–1701. http://dx.doi.org/10.1002/2016WR019396.

Barker, L., Hannaford, J., Parry, S., 2016. Briefing Note: Severity of the December 2015 floods – preliminary analysis [WWW Document]. Cent. Ecol. Hydrol http://www.ceh.ac.uk/news-and-media/blogs/briefing-note-severity-december-2015-floods-preliminary-analysis (accessed 11.15.16).

Baruch, A., May, A., Yu, D., 2016. The motivations, enablers and barriers for voluntary participation in an online crowdsourcing platform. Comput. Hum. Behav. 64, 923–931. http://dx.doi.org/10.1016/j.chb.2016.07.039.

Bates, P.D., De Roo, A.P.J., 2000. A simple raster-based model for flood inundation simulation. J. Hydrol. 236, 54–77. http://dx.doi.org/10.1016/S0022-1694(00)00278-X.

Bates, P.D., Horritt, M.S., Fewtrell, T.J., 2010. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. J. Hydrol. 387, 33–45. http://dx.doi.org/10.1016/j.jhydrol.2010.03.027.

Bradbrook, K.F., Lane, S.N., Waller, S.G., Bates, P.D., 2004. Two dimensional diffusion wave modelling of flood inundation using a simplified channel representation. Int. J. River Basin Manage. 2, 211–223. http://dx.doi.org/10.1080/15715124.2004.9635233.

Brandeis, M.-N.W., Carrera Zamanillo, M.I., 2017. Finding meaningful participation in volunteer geographic information and citizen science: a case comparison in environmental application. Cartogr. Geogr. Inf. Sci. 44, 539–550. http://dx.doi.org/10.1080/15230406.2016.1221779.

Charmaz, K., 2011. A Constructivist Grounded Theory Analysis of Losing and Regaining a Valued Self. In: Wertz, F.J. (Ed.), Five Ways of Doing Qualitative Analysis : Phenomenological Psychology, Grounded Theory, Discourse Analysis, Narrative Research, and Intuitive Inquiry. Guilford Press, New York, pp. 165–204.

Chow, V.T., 1959. Open-Channel Hydraulics. McGraw-Hill civil engineering series, McGraw-Hill, New York.

Clark, A., Emmel, N., 2008. Walking interviews: more than walking and talking. Presented at the "Peripatetic Practices": a workshop on walking, London.

Cobby, D.M., Mason, D.C., Horritt, M.S., Bates, P.D., 2003. Two-dimensional hydraulic flood modelling using a finite-element mesh decomposed according to vegetation and topographic features derived from airborne scanning laser altimetry. Hydrol. Process. 17, 1979–2000. http://dx.doi.org/10.1002/hyp.1201.

Coles, D., Yu, D., Wilby, R.L., Green, D., Herring, Z., 2017. Beyond "flood hotspots": Modelling emergency service accessibility during flooding in York. UK. J. Hydrol. 546, 419–436. http://dx.doi.org/10.1016/j.jhydrol.2016.12.013.

Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., Böhner, J., 2015. System for automated geoscientific analyses (SAGA) v. 2.1.4. Geosci. Model Dev. 8, 1991–2007. http://dx.doi.org/10.5194/gmd-8-1991-2015.

Cope, M., Elwood, S., 2009. Introduction: Qualitative GIS: Forging Mixed Methods through Representations, Analytical Innovations, and Conceptual Engagements. In: Cope, M., Elwood, S. (Eds.), Qualitative GIS: A Mixed Methods Approach. Sage, Thousand Oaks, CA, pp. 1–12.

Crower, R.A., 2009. Fluvial Design Guide Chapter 7 Hydraulic analysis and design.

Degrossi, L., De Albuquerque, J., Fava, M., Mendiondo, E., 2014. Flood Citizen Observatory: a crowdsourcing-based approach for flood risk management in Brazil.

Dowling, R., Lloyd, K., Suchet-Pearson, S., 2016. Qualitative methods 1: enriching the interview. Prog. Hum. Geogr. 40, 679–686. http://dx.doi.org/10.1177/0309132515596880.

Environment Agency, 2016. Impact Report Winter Flooding 2015-16 - Northumberland, Durham and Tees Area.

Evans, J., Jones, P., 2011. The walking interview: Methodology, mobility and place. Appl. Geogr. 31, 849–858. http://dx.doi.org/10.1016/j.apgeog.2010.09.005.

Fernández, A., Najafi, M.R., Durand, M., Mark, B.G., Moritz, M., Jung, H.C., Neal, J., Shastry, A., Laborde, S., Phang, S.C., Hamilton, I.M., Xiao, N., 2016. Testing the skill of numerical hydraulic modeling to simulate spatiotemporal flooding patterns in the

Logone floodplain. Cameroon J. Hydrol. 539, 265–280. http://dx.doi.org/10.1016/j.jhydrol.2016.05.026.
García-Pintado, J., Neal, J.C., Mason, D.C., Dance, S.L., Bates, P.D., 2013. Scheduling satellite-based SAR acquisition for sequential assimilation of water level observations into flood modelling. J. Hydrol. 495, 252–266. http://dx.doi.org/10.1016/j.jhydrol.2013.03.050.
Gobeyn, S., Van Wesemael, A., Neal, J., Lievens, H., Adams, K., De Vleeschouwer, N., Vernieuwe, H., Schumann, G.J.P., Di Baldassarre, G., Baets, B., Bates, P.D., Verhoest, N.E.C., 2017. Impact of the timing of a SAR image acquisition on the calibration of a flood inundation model. Adv. Water Resour. 100, 126–138. http://dx.doi.org/10.1016/j.advwatres.2016.12.005.
Goodchild, M.F., 2007. Citizens as sensors: the world of volunteered geography. GeoJ. 69, 211–221. http://dx.doi.org/10.1007/s10708-007-9111-y.
Goodchild, M.F., Glennon, J.A., 2010. Crowdsourcing geographic information for disaster response: a research frontier. Int. J. Digit. Earth 3, 231–241. http://dx.doi.org/10.1080/17538941003759255.
Granell, C., Ostermann, F.O., 2016. Beyond data collection: Objectives and methods of research using VGI and geo-social media for disaster management. Comput. Environ. Urban Syst. 59, 231–243. http://dx.doi.org/10.1016/j.compenvurbsys.2016.01.006.
Haklay, M., Antoniou, V., Basiouka, S., Soden, R., Mooney, P., 2014. Crowdsourced geographic information use in government (Report to GFDRR). World Bank, London.
Hardy, R.J., Bates, P.D., Anderson, M.G., 1999. The importance of spatial resolution in hydraulic models for floodplain environments. J. Hydrol. 216, 124–136. http://dx.doi.org/10.1016/S0022-1694(99)00002-5.
Haworth, B., Bruce, E., 2015. A Review of Volunteered Geographic Information for Disaster Management: a Review of VGI for Disaster Management. Geogr. Compass 9, 237–250. http://dx.doi.org/10.1111/gec3.12213.
Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nat. Clim. Change 3. http://dx.doi.org/10.1038/nclimate1911.
Horita, F.E.A., de Albuquerque, J.P., Degrossi, L.C., Mendiondo, E.M., Ueyama, J., 2015. Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks. Comput. Geosci. 80, 84–94. http://dx.doi.org/10.1016/j.cageo.2015.04.001.
Horritt, M., Bates, P.D., 2001. Effects of spatial resolution on a raster based model of flood flow. J. Hydrol. 253, 239–249. http://dx.doi.org/10.1016/S0022-1694(01)00490-5.
Hung, K.-C., Kalantari, M., Rajabifard, A., 2016. Methods for assessing the credibility of volunteered geographic information in flood response: A case study in Brisbane, Australia. Appl. Geogr. 68, 37–47. http://dx.doi.org/10.1016/j.apgeog.2016.01.005.
Hunter, N.M., Bates, P.D., Horritt, M.S., Wilson, M.D., 2007. Simple spatially-distributed models for predicting flood inundation: a review. Geomorphology 90, 208–225. http://dx.doi.org/10.1016/j.geomorph.2006.10.021.
Hunter, N.M., Horritt, M.S., Bates, P.D., Wilson, M.D., Werner, M.G.F., 2005. An adaptive time step solution for raster-based storage cell modelling of floodplain inundation. Adv. Water Resour. 28, 975–991. http://dx.doi.org/10.1016/j.advwatres.2005.03.007.
Jung, Y., Kim, D., Kim, D., Kim, M., Lee, S.O., 2014. Simplified flood inundation mapping based on flood elevation-discharge rating curves using satellite images in gauged watersheds. Water 6, 1280–1299. http://dx.doi.org/10.3390/w6051280.
Klonner, C., Marx, S., Usán, T., Porto de Albuquerque, J., Höfle, B., 2016. Volunteered geographic information in natural hazard analysis: a systematic literature review of current approaches with a focus on preparedness and mitigation. ISPRS Int. J. Geo-Inf. 5, 103. http://dx.doi.org/10.3390/ijgi5070103.
Knigge, L., Cope, M., 2006. Grounded visualization: integrating the analysis of qualitative and quantitative data through grounded theory and visualization. Environ. Plan. A 38, 2021–2037. http://dx.doi.org/10.1068/a37327.
Kusenbach, M., 2003. Street phenomenology: the Go-Along as ethnographic research tool. Ethnography 4, 455–485. http://dx.doi.org/10.1177/146613810343007.
Lane, S.N., Landström, C., Whatmore, S.J., 2011a. Imagining flood futures: risk assessment and management in practice. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 369, 1784–1806. http://dx.doi.org/10.1098/rsta.2010.0346.
Lane, S.N., Odoni, N., Landström, C., Whatmore, S.J., Ward, N., Bradley, S., 2011b. Doing flood risk science differently: an experiment in radical scientific method. Trans. Inst. Br. Geogr. 36, 15–36. http://dx.doi.org/10.1111/j.1475-5661.2010.00410.x.
Lanfranchi, V., Wrigley, S.N., Ireson, N., Ciravegna, F., Wehn, U., 2014. Citizens' Observatories for Situation Awareness in Flooding, in: Proceedings of the 11th International ISCRAM Conference. Pennsylvania.
Lee, M., Abbot, C., 2003. The usual suspects? public participation under the Aarhus convention. Mod. Law Rev. 66, 80–108. http://dx.doi.org/10.1111/1468-2230.6601004.
Marsh, T., Kirby, C., Muchan, K., Barker, L., Henderson, E., Hannaford, J., 2016. The winter floods of 2015/2016 in the UK – a review. Centre for Ecology and Hydrology, Wallingford.
Mays, N., Pope, C., 2000. Assessing quality in qualitative research. BMJ 320, 50–52. http://dx.doi.org/10.1136/bmj.320.7226.50.
McCallum, I., Liu, W., See, L., Mechler, R., Keating, A., Hochrainer-Stigler, S., Mochizuki, J., Fritz, S., Dugar, S., Arestegui, M., Szoenyi, M., Bayas, J.-C.L., Burek, P., French, A., Moorthy, I., 2016. Technologies to support community flood disaster risk reduction. Int. J. Disaster Risk Sci. 7, 198–204. http://dx.doi.org/10.1007/s13753-016-0086-5.
McDougall, K., 2012. An assessment of the contribution of volunteered geographic information during recent natural disasters. In: Rajabifard, A., Coleman, D. (Eds.), Spatially Enabling Government, Industry and Citizens: Research and Development Perspectives. GSDI Association Press, Needham, MA, United States, pp. 201–214.
Muller, C., Chapman, l., Johnston, L., Kidd, S., Illingworth, C., Foody, S., Overeem, G., Leigh, A., 2015. Crowdsourcing for climate and atmospheric sciences: current status and future potential. Int. J. Climatol. 35, 3185–3203. http://dx.doi.org/10.1002/joc.4210.
Munich Re, 2013. Floods dominate natural catastrophe statistics in first half of 2013 [WWW Document]. URL https://www.munichre.com/en/media-relations/publications/press-releases/2013/2013-07-09-press-release/index.html (accessed 10.28.17).
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — a discussion of principles. J. Hydrol. 10, 282–290. http://dx.doi.org/10.1016/0022-1694(70)90255-6.
National Research Council, 2008. Public Participation in Environmental Assessment and Decision Making. National Academies Press.
Neal, J., Schumann, G., Bates, P.D., 2012. A subgrid channel model for simulating river hydraulics and floodplain inundation over large and data sparse areas. Water Resour. Res. 48. http://dx.doi.org/10.1029/2012WR012514.
Neal, J., Schumann, G., Fewtrell, T., Budimir, M., Bates, P.D., Mason, D., 2011. Evaluating a new LISFLOOD-FP formulation with data from the summer 2007 floods in Tewkesbury, UK: Evaluating a new LISFLOOD-FP formulation. J. Flood Risk Manage. 4, 88–95. http://dx.doi.org/10.1111/j.1753-318X.2011.01093.x.
Neal, J.C., Bates, P.D., Fewtrell, T.J., Hunter, N.M., Wilson, M.D., Horritt, M.S., 2009. Distributed whole city water level measurements from the Carlisle 2005 urban flood event and comparison with hydraulic model simulations. J. Hydrol. 368, 42–55. http://dx.doi.org/10.1016/j.jhydrol.2009.01.026.
S. Néelz G. Pender 2013 Benchmarking the latest generation of 2D hydraulic modelling packages (No. SC120002) Environment Agency Bristol.
Nester, T., Komma, J., Blöschl, G., 2016. Real time flood forecasting in the Upper Danube basin. J. Hydrol. Hydromech. 64, 404–414. http://dx.doi.org/10.1515/johh-2016-0033.
Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., Crowston, K., 2012. The future of citizen science: emerging technologies and shifting paradigms. Front. Ecol. Environ. 10, 298–304. http://dx.doi.org/10.1890/110294.
Pappenberger, F., Beven, K., Frodsham, K., Romanowicz, R., Matgen, P., 2007a. Grasping the unavoidable subjectivity in calibration of flood inundation models: a vulnerability weighted approach. J. Hydrol. 333, 275–287. http://dx.doi.org/10.1016/j.jhydrol.2006.08.017.
Pappenberger, F., Frodsham, K., Beven, K., Romanowicz, R., Matgen, P., 2007b. Fuzzy set approach to calibrating distributed flood inundation models using remote sensing observations. Hydrol. Earth Syst. Sci. 11, 739–752. http://dx.doi.org/10.5194/hess-11-739-2007.
Parkes, B.L., Cloke, H.L., Pappenberger, F., Neal, J., Demeritt, D., 2013. Reducing inconsistencies in point observations of maximum flood inundation level. Earth Interact. 17, 1–27. http://dx.doi.org/10.1175/2012EI000475.1.
Perks, M.T., Russell, A.J., Large, A.R.G., 2016. Technical note: advances in flash flood monitoring using unmanned aerial vehicles (UAVs). Hydrol. Earth Syst. Sci. 20, 4005–4015. http://dx.doi.org/10.5194/hess-20-4005-2016.
Refsgaard, J.C., Henriksen, H.J., 2004. Modelling guidelines—terminology and guiding principles. Adv. Water Resour. 27, 71–82. http://dx.doi.org/10.1016/j.advwatres.2003.08.006.
Renschler, C.S., Wang, Z., 2017. Multi-source data fusion and modeling to assess and communicate complex flood dynamics to support decision-making for downstream areas of dams: the 2011 hurricane irene and schoharie creek floods, NY. Int. J. Appl. Earth Obs. Geoinformation 62, 157–173. http://dx.doi.org/10.1016/j.jag.2017.06.002.
Reynard, N.S., Kay, A.L., Anderson, M., Donovan, B., Duckworth, C., 2017. The evolution of climate change guidance for fluvial flood risk management in England. Prog. Phys. Geogr. 41, 222–237. http://dx.doi.org/10.1177/0309133317702566.
Rollason, E., Bracken, L.J., Hardy, R.J., Large, A.R.G., 2018. Rethinking flood risk communication. Nat. Hazards 1–22. http://dx.doi.org/10.1007/s11069-018-3273-4.
Ruiz-Mallén, I., Riboli-Sasco, L., Ribrault, C., Heras, M., Laguna, D., Perié, L., 2016. Citizen Science: Toward Transformative Learning. Sci. Commun. 38, 523–534. http://dx.doi.org/10.1177/1075547016642241.
Rykiel, E.J., 1996. Testing ecological models: the meaning of validation. Ecol. Model. 90, 229–244. http://dx.doi.org/10.1016/0304-3800(95)00152-2.
Sampson, C.C., Fewtrell, T.J., Duncan, A., Shaad, K., Horritt, M.S., Bates, P.D., 2012. Use of terrestrial laser scanning data to drive decimetric resolution urban inundation models. Adv. Water Resour. 41, 1–17. http://dx.doi.org/10.1016/j.advwatres.2012.02.010.
Sampson, C.C., Smith, A.M., Bates, P.D., Neal, J.C., Alfieri, L., Freer, J.E., 2015. A high-resolution global flood hazard model. Water Resour. Res. 51, 7358–7381. http://dx.doi.org/10.1002/2015WR016954.
Savage, J.T.S., Bates, P.D., Freer, J.E., Neal, J.C., Aronica, G.T., 2016. When does spatial resolution become spurious in probabilistic flood inundation predictions? Hydrol. Process. 30, 2014–2032. http://dx.doi.org/10.1002/hyp.10749.
Schnebele, E., Cervone, G., 2013. Improving remote sensing flood assessment using volunteered geographical data. Nat Hazards Earth Syst Sci 13, 669–677. http://dx.doi.org/10.5194/nhess-13-669-2013.
Segura-Beltrán, F., Sanchis-Ibor, C., Morales-Hernández, M., González-Sanchis, M., Bussi, G., Ortiz, E., 2016. Using post-flood surveys and geomorphologic mapping to evaluate hydrological and hydraulic models: the flash flood of the Girona River (Spain) in 2007. J. Hydrol. 541, 310–329. http://dx.doi.org/10.1016/j.jhydrol.2016.04.039.
Simonovic, S.P., Ahmad, S., 2005. Computer-based Model for flood evacuation emergency planning. Nat. Hazards 34, 25–51. http://dx.doi.org/10.1007/s11069-004-0785-x.
Smith, K.W., 2015. Drone technology: benefits, risks, and legal considerations. Seattle J. EnvironLaw SJEL 5 [i]–302.
Smith, R.A.E., Bates, P.D., Hayes, C., 2012. Evaluation of a coastal flood inundation model using hard and soft data. Environ. Model. Softw. 30, 35–46. http://dx.doi.org/10.1016/j.envsoft.2011.11.008.
Sousa, D., 2014. Validation in qualitative research: general aspects and specificities of the

descriptive phenomenological method. Qual. Res. Psychol. 11, 211–227. http://dx.doi.org/10.1080/14780887.2013.853855.
Starkey, E., Parkin, G., Birkinshaw, S., Large, A., Quinn, P., Gibson, C., 2017. Demonstrating the value of community-based ("citizen science") observations for catchment modelling and characterisation. J. Hydrol. 548, 801–817. http://dx.doi.org/10.1016/j.jhydrol.2017.03.019.
Tang, Z., Zhou, Y., Yu, H., Gu, Y., Liu, T., 2017. Developing an interactive mobile volunteered geographic information platform to integrate environmental big data and citizen science in urban management. In: Seeing Cities Through Big Data. Springer Geography. Springer, Cham, pp. 65–81.
Teng, J., Jakeman, A.J., Vaze, J., Croke, B.F.W., Dutta, D., Kim, S., 2017. Flood inundation modelling: a review of methods, recent advances and uncertainty analysis. Environ. Model. Softw. 90, 201–216. http://dx.doi.org/10.1016/j.envsoft.2017.01.006.
Triglav-Cekada, M., Radovan, D., 2013. Using volunteered geographical information to map the November 2012 floods in Slovenia. Nat. Hazards Earth Syst. Sci. 13, 2753–2762. http://dx.doi.org/10.5194/nhess-13-2753-2013.
Usón, T.J., Klonner, C., Höfle, B., 2016. Using participatory geographic approaches for urban flood risk in Santiago de Chile: insights from a governance analysis. Environ. Sci. Policy 66, 62–72. http://dx.doi.org/10.1016/j.envsci.2016.08.002.
Wan, Z., Hong, Y., Khan, S., Gourley, J., Flamig, Z., Kirschbaum, D., Tang, G., 2014. A cloud-based global flood disaster community cyber-infrastructure: development and demonstration. Environ. Model. Softw. 58, 86–94. http://dx.doi.org/10.1016/j.envsoft.2014.04.007.
Wehn, U., Rusca, M., Evers, J., Lanfranchi, V., 2015. Participation in flood risk management and the potential of citizen observatories: a governance analysis. Environ. Sci. Policy 48, 225–236.
Wiggins, A., He, Y., 2016. Community-based Data Validation in Citizen Science. https://doi.org/10.13016/M2N733.
Wing, O.E.J., Bates, P.D., Sampson, C.C., Smith, A.M., Johnson, K.A., Erickson, T.A., 2017. Validation of a 30 m resolution flood hazard model of the conterminous United States. Water Resour. Res. http://dx.doi.org/10.1002/2017WR020917.
Wood, M., Hostache, R., Neal, J.C., Wagener, T., Giustarini, L., Chini, M., Corato, G., Matgen, P., Bates, P.D., 2016. Calibration of channel depth and friction parameters in the LISFLOOD-FP hydraulic model using medium-resolution SAR data and identifiability techniques. Hydrol. Earth Syst. Sci. 20, 4983–4997. http://dx.doi.org/10.5194/hess-20-4983-2016.

Nat Hazards
https://doi.org/10.1007/s11069-018-3273-4

ORIGINAL PAPER

Rethinking flood risk communication

E. Rollason[1] · L. J. Bracken[1] · R. J. Hardy[1] · A. R. G. Large[2]

Received: 29 June 2017 / Accepted: 11 March 2018

Abstract Flooding is a serious hazard across Europe, with over 200 major floods documented in the last two decades. Over this period, flood management has evolved, with a greater responsibility now placed on at-risk communities to understand their risk and take protective action to develop flood resilience. Consequently, communicating flood risk has become an increasingly central part of developing flood resilience. However, research suggests that current risk communications have not resulted in the intended increase in awareness, or behavioural change. This paper explores how current risk communications are used by those at risk, what information users desire and how best this should be presented. We explore these questions through a multi-method participatory experiment, working together with a competency group of local participants in the town of Corbridge, Northumberland, the UK. Our research demonstrates that current risk communications fail to meet user needs for information in the period before a flood event, leaving users unsure of what will happen, or how best to respond. We show that participants want information on when and how a flooding may occur (flood dynamics), so that they can understand their risk and feel in control of their decisions on how to respond. We also present four prototypes which translate these information needs into new approaches to communicating flood risk. Developed by the research participants, these proposals meet their information needs, increase their flood literacy and develop their response capacity. The findings of the research have implications for how we design and develop future flood communications, but also for how we envisage the role of flood communications in developing resilience at a community level.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11069-018-3273-4) contains supplementary material, which is available to authorized users.

E. Rollason
e.d.rollason@durham.ac.uk

[1] Science Laboratories, Department of Geography, Durham University, South Rd, Durham DH1 3LE, UK

[2] School of Geography, Politics and Sociology, Newcastle University, Newcastle upon Tyne NE1 7RU, UK

Published online: 19 March 2018

Keywords Flood risk · Resilience · Flood mapping · Communication · Participation

1 Introduction

Flooding is a major hazard throughout Europe (de Moel et al. 2009), with over 2.4 million properties potentially at risk in the UK alone (Environment Agency 2009). Over the last decade flood risk management (FRM) has evolved to develop and enhance community resilience to flooding, rather than controlling flood waters using engineering solutions (Van Alphen et al. 2009). Communication of flood risk information is a key element of FRM which aims to 'strengthen people's risk awareness and to motivate the population at risk to take preventive actions and to be prepared' (Hagemeier-Klose and Wagner 2009, p. 564). Communication of flood risk is a valuable way to link expertise and management undertaken by practitioners with the development of local-level resilience in an at risk community (de Moel et al. 2009; Butler and Pidgeon 2011).

Flood risk communication encompasses two phases: firstly, identifying areas at risk of flooding, and secondly, letting those at risk know when flooding is likely to occur. Both phases are crucial to helping those at risk prepare for, anticipate and act to lessen the consequences of flood events. This is a vital element of developing community resilience; flood impacts can be significant, extending beyond those whose homes are directly flooded, and for prolonged periods following a flooding event. For instance, research has demonstrated that flooding can result in increased morbidity (Milojevic et al. 2017), increase the occurrence of infectious diseases (Waite et al. 2017), and cause significant, long-term mental health impacts (Lamond et al. 2015) including depression, anxiety and post-traumatic stress disorder (Munro et al. 2017). As well as helping people take action to reduce the impact of floods on their homes and to evacuate areas of high flood hazard, flood risk communications have also been shown to have a significant impact on reducing longer-term impacts. For example, Munro et al. (2017) demonstrate that receiving timely warning prior to a flood was the only factor likely to limit the impact of flooding on mental health. Communicating flood risk prior to, and during flood events, is thus crucial to limiting flood impacts and ensuring well-being in at-risk communities.

This paper explores current flood risk communications and their effectiveness in promoting resilient behaviours, and introduces new ways in which information could be presented to increase action to limit flood impacts. This assessment focuses on the approaches adopted in Europe following the introduction of the European Union Floods Directive (EUFD) (European Parliament and the Council 2007), which has resulted in a unification of communication approaches between countries within the EU. We employ a case study in the UK, where we work with a community that have previous experiences of flooding to (1) examine existing approaches to flood communications, (2) explore how we can work with at risk participants to develop new ways of thinking about the content of flood risk communication, and (3) use participatory approaches to co-produce a series of prototypes for more effective flood risk communications.

Research in psychology has explored the way in which risk messages are translated into behaviour by those receiving them (for example, see Slovic et al. 1974; Fischhoff et al. 1993; Burns and Slovic 2012; Bubeck et al. 2012). However, in the translation of this research into risk communication practice, those at risk are often framed as needy, and reliant on experts to dictate what risk information is important and why (Willis et al. 2011). This means at risk communication users are often excluded from the processes of creating risk communications. By adopting participatory practices, and working together with those at risk, the research presented in this paper looks to circumvent this framing by allowing research participants to determine what information is important to them for understanding their risk and increasing their resilience.

2 Current approaches to communications in flood risk management

Across Europe, the 2007 EUFD established common standards for the preparation of flood hazard and flood risk maps (EXCIMAP 2007a). The UK provides a good example of these products, with the Environment Agency (EA) publishing a well-developed suite of different mapping types available online (de Moel et al. 2009), alongside an array of supporting communications (Table 1). These include communication of real-time river levels, and flood alerts and warnings intended to highlight the short-term potential for flooding.

The EA's prime purpose for flood risk communications is to encourage participation in local FRM and develop community resilience (Environment Agency 2011). EA research on resilience has previously focused on generating trusted, long-term relationships with at-risk communities (Twigger-Ross et al. 2011, 2014) (Table 1). As a result, communications have traditionally been supported by a network of local flood groups and wardens, tasked with working alongside the EA to prepare local communities for flooding (Gilissen et al. 2016). However, recent high-profile floods have caused a shift of focus towards infrastructure and property-based resilience programmes (McBain et al. 2010; Chatterton et al. 2010; Environment Agency 2011). As a result, community-based resilience has become somewhat of a secondary objective and the potential for risk communications as an enabler of resilience has taken on a much greater level of importance (Environment Agency 2010). However, the existing research suggests that current communications are having limited impact on driving risk awareness or resilient behaviours. O'Sullivan et al. (2012) examined the impact of flood risk communications across Europe and identified low levels of information penetration and personal preparedness, often accompanied by a high level of

Table 1 Flood risk communications approaches in England and Wales

Communications approach	Description and purpose of the communications
Flood hazard and risk maps	These online maps indicate areas of potential flood hazard and differentiate high-, medium- and low-risk categories. Intended to raise awareness of the risk of flooding of those living in at-risk areas Common to the majority of countries in the EU (EXCIMAP 2007a, b; de Moel et al. 2009)
Real-time water level information	Hydrographs of 'real-time' river levels monitored at river gauging stations provided online. During flooding conditions these records are updated at 15-min intervals. These hydrographs also display the level over which flooding can be expected and the highest level ever recorded. Intended to allow local people to monitor local river levels and decide when to take action in response to potential flooding
Flood warnings (Flood Information Service)	A flood warning system is also implemented across England (Fielding et al. 2007). Three alert levels are provided, the intention being that those at risk should begin to monitor local river levels at the Flood Alert Stage and begin to implement flood-resilient actions at a Flood Warning Stage. Intended to instruct those at risk when to take action in response to a potential flood

distrust in communications and management organisations. In the UK, a 2016 EA poll indicated that only 45% of people living in at-risk areas appreciate their risk and only 7% identify any risk to their own property (Environment, Food and Rural Affairs Select Committee 2016). Similarly, independent polling by the '*Know Your Flood Risk*' campaign (Davies 2015) reported that 31% of at risk households surveyed had no flood plan and would not know what to do in the event of flooding.

3 Risk communication approaches and the adoption of resilient behaviours

Research has therefore identified that the existing UK model of flood risk communication is not functioning as intended, with communications failing to meet user needs or match their experiential knowledge (Environment Agency 2010; Meyer et al. 2012; Fisher 2015). It has also been argued that by centralising and professionalising the production of risk information, local communities lose their ability to properly understand their local risk situation (Lane 2012; Bubeck et al. 2012). The outcome is that both the practice of communicating risk information and how information receivers interpret information may not actually be aligned with the stated purpose of flood risk communications in the UK. In this section we explore the fundamental research that underpins risk communication and examine why this might be the case.

Callon (1999) and Demeritt and Norbert (2014) have both proposed models for how risk is communicated, considering the direction of communication, the roles of the communicator and the receiver, and the purpose of the communication (Table 2).

Flood risk communications have a joint purpose of both transmitting information and also altering behaviour (Hagemeier-Klose and Wagner 2009) and can therefore be seen as a hybrid of the risk message model (RMM) or the public education model (PEM), and the risk information model (RIM). Research driving RIM-focused communications has explored a wide range of potential factors which influence the translation of risk information into behaviours: examples include previous experiences of a threat (Fielding et al. 2007; Hopkins and Warburton 2015); cultural, geographical, and socio-economic factors (Burningham et al. 2008; Bubeck et al. 2012); reliance on public flood protection (Terpstra and Gutteling 2008); trust/distrust in communications from a management authority (Terpstra 2011; Wachinger et al. 2013); or a need to protect an individual's sense of personal security against high levels of future uncertainty (Harries 2008; Willis et al. 2011).

An alternative approach to examining individual variables is proposed by Rogers (1975), who presents the protection motivation theory (PMT) model (Fig. 1). PMT explains and provides an overarching framework for the interplay between the disparate variables which may contribute to triggering behavioural responses from risk information. Rogers argues that individuals make their decision by appraising the severity and likelihood of their exposure (the threat appraisal) against the potential efficacy of potential protective behaviours (the coping appraisal), with their protection motivation representing the intervening stimulus which determines their actions.

Grothmann and Reusswig (2006) and Bubeck et al. (2012) build upon Roger's work by expanding the sub-components of the threat and coping appraisals (Fig. 1), as well as identifying the potential for non-protective responses such as denial or wishful thinking, in situations where threat and/or coping appraisals are negative. This concept is supported

Table 2 A comparison of the defining characteristics of risk communications models proposed by Callon (1999) and Demerit and Norbert (2014)

Model	Direction	Role of communicators	Role of receivers	Purpose of communication
Demerit and Norbert				
Risk message	One	Educator	Passive	To inform[a]
Risk instrument	One	Educator	Passive	Behavioural alteration
Risk dialogue	Two	Active participant	Active participant[b]	To inform Behavioural alteration
Risk governance	Integrated[c]	Active participant	Active participant	Encourage participation Create new knowledge/viewpoints
Callon				
Public education	One	Educator	Passive	To inform[a]
Public debate	Two	Active participant[d]	Active participant[e]	To inform[a]
Co-production of knowledge	Integrated[b]	Active participant	Active participant	Create shared knowledge/viewpoints[f]

[a]Assumes rational action from receivers

[b]Who should participate, why and how is seen as contested and dependent upon the purpose of the communication

[c]Blurring of roles between knowledge producers and receivers

[d]Privileged knowledge producers

[e]Local knowledge intended to enrich scientific knowledge

[f]Development of knowledge and viewpoints which are developed through the participatory process and are therefore shared by all participants

by research on ‘learned helplessness’ (Paton and Johnston 2001), where individuals see disaster events as uncontrollable and therefore assume that their impacts are in turn uncontrollable, triggering feelings of despair or helplessness (Paton and Johnston 2006).

PMT demonstrates the complex, contested, and highly personal nature of the linkage between communication and the adoption of protective behaviours. Comparison against the models of communication reveals the likely limitations of current communication approaches based on the RIM or PEM. These approaches, which assume a rational response from the receiver, are unlikely to address the complex nature of the threat and coping appraisals.

4 Using participatory approaches to developing new ways to communicate flood risk

We suggest that participatory working (Kindon et al. 2007) offers an opportunity to rethink how information can be communicated to those at risk by positioning people at the heart of flood risk communications. Participatory working re-imagines the traditional roles of experts and lay people (Bucchi and Neresini 2008; Landström et al. 2011; Lane et al. 2011) and considers circulation of different forms of expertise (Whitman et al. 2015), with participants working together as equals to co-produce shared knowledge and outputs (Mees

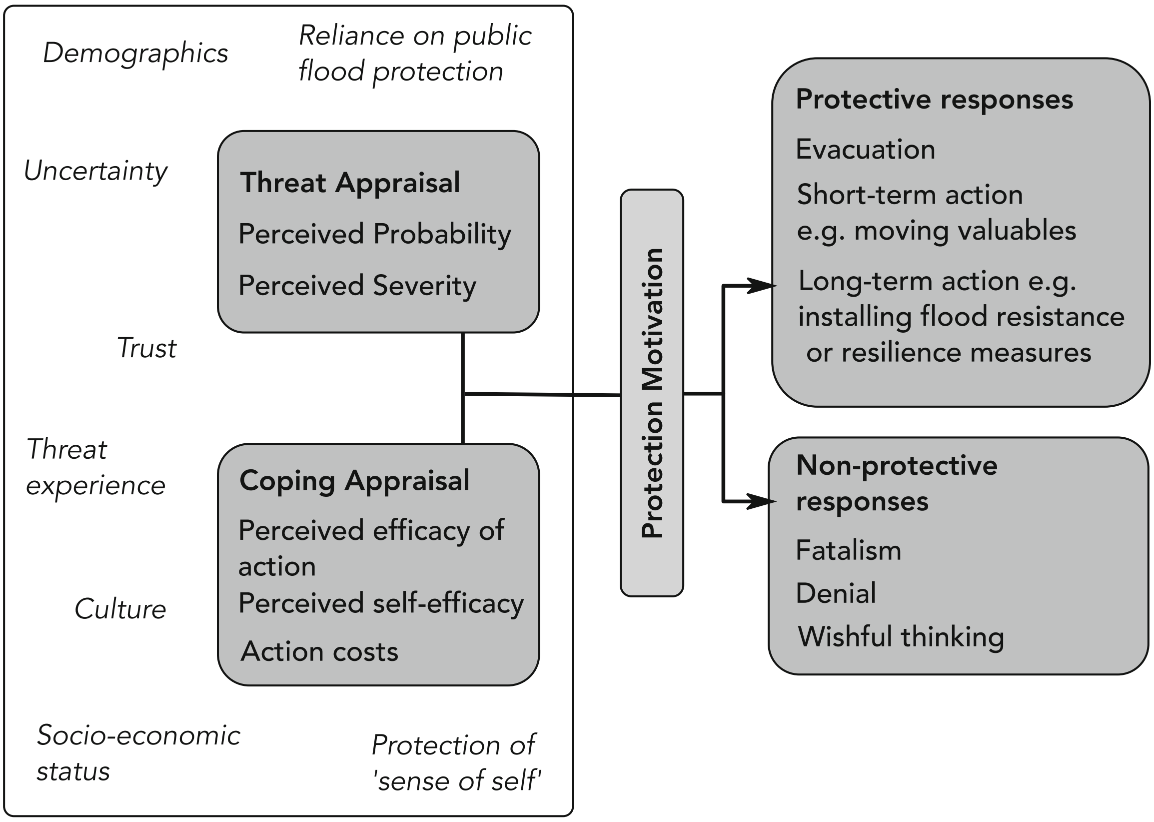


Fig. 1 The protection motivation theory model. Factors influencing a decision to take protective or non-protective action in response to a threat. Shaded areas denote the PMT as proposed by Rogers (1975) and developed by Bubeck et al. (figure adapted from Bubeck et al. 2012), whilst unshaded areas denote individual factors which have been shown to impact on threat and coping appraisals and therefore an individual's protection motivation

et al. 2016). Participatory working approaches have been applied to a variety of environmental problems, including the co-production of options for managing local flood risk (Lane et al. 2011), the breaking down of borders between different organisations, professionals, and lay people involved in catchment-scale land management to manage floods (Bracken et al. 2016), and developing end-user specific research outputs regarding agricultural pollution (Whitman et al. 2015). To date, however, participatory practices have not been applied to flood risk communications, with recent research concluding only that participation was a useful approach for raising awareness or communicating flood risk complexity (Environment Agency 2012), or as a way of providing limited feedback on current communication approaches (Fisher 2015). These limited approaches to participation fail to exploit the potential of participatory working to open up the debate on what risk information is important and why. Here therefore we look to expand the participatory approaches demonstrated by previous studies into exploring the efficacy of current flood communications and, working together with a flood group of flood-affected locals, to co-produce alternative communications better suited to driving resilient behaviours.

4.1 The Corbridge study area

Corbridge (Fig. 2) has a long history of flooding; approximately 70 properties in Station Road and The Stanners are situated on the floodplain and are vulnerable to flooding. River level records date back to the 1700s (Archer et al. 2007a), and the area has a long history of

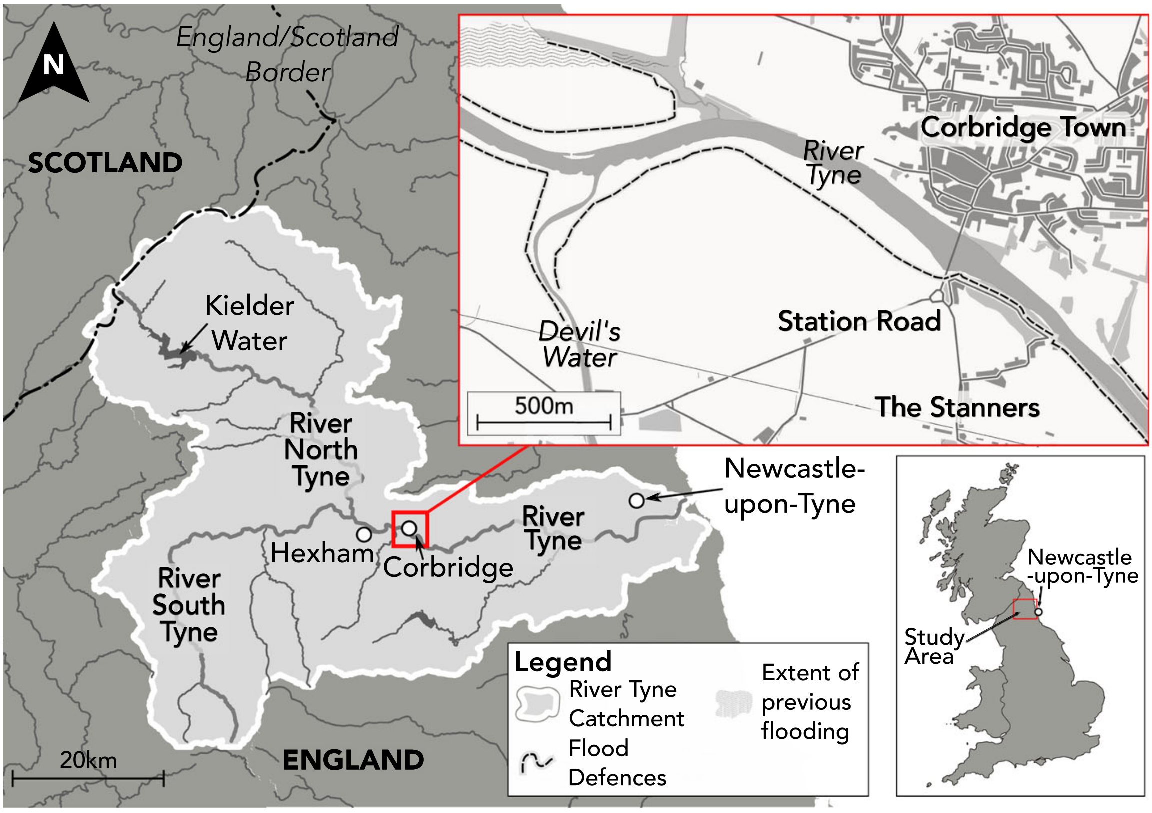


Fig. 2 The River Tyne catchment and Corbridge study area. The inset highlights the extent of the area considered during the research

flooding, including flooding in 2005 resulting from the collapse of a flood defence embankment (Archer et al. 2007b). This earlier damage led to flood defence improvements being carried out by the EA prior to a major flood on 5 December 2015, an event with an estimated return period of between 100 and 200 years (Marsh et al. 2016), which exceeded the design standard for the defences leading to serious flooding. All 70 at-risk properties were reported to have been flooded (Environment Agency 2016), some to depths of > 1.5 m.

4.2 The research approach

In the summer of 2016, we undertook research to explore local knowledge about flooding in the Tyne Valley based on working together with local people to develop new approaches to communicating risk. Our aim was to blend academic research expertise with the experiences of Corbridge residents to re-imagine what flood risk information could be communicated and how it might be best presented. Figure 3 shows the multi-methods participatory approach developed.

4.2.1 Understanding local knowledge and flood experience: workshops with the Corbridge Flood Action Group

In Phase 1 we conducted several group mapping and discussion workshops with members of the local Corbridge Flood Action Group (CFAG). The purpose of these meetings was to assess local knowledge and experiences of flood risk. Using a grounded theory approach, following Charmaz (2011), the material produced by these workshops, the maps, the researchers' notes and the group discussions were integrated to identify key themes arising

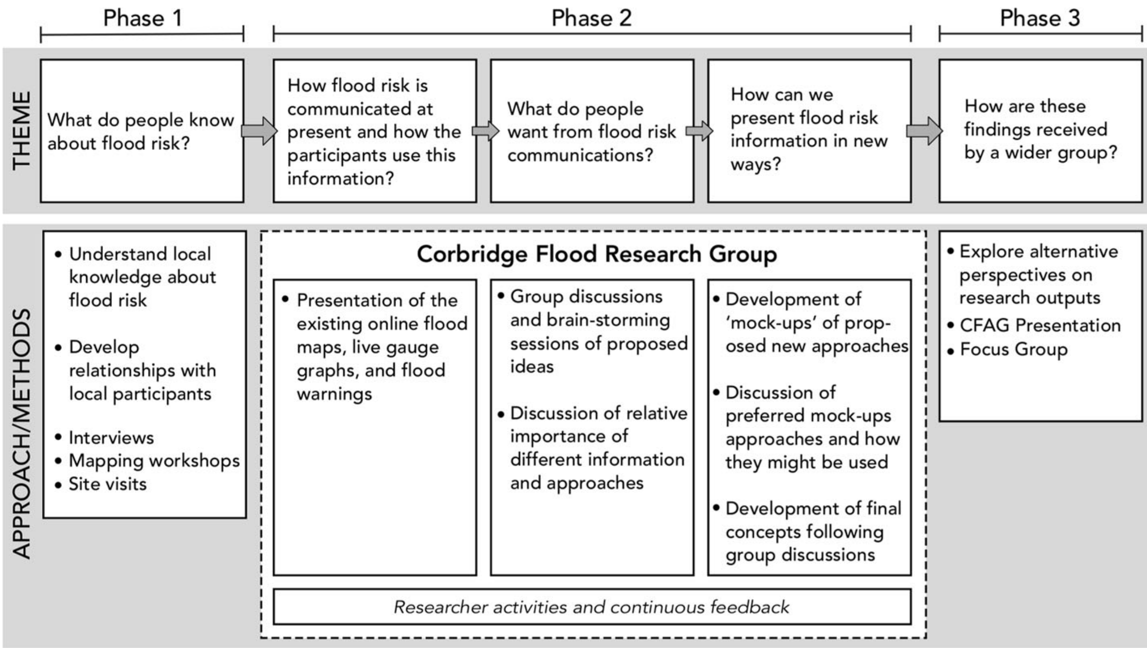


Fig. 3 The multi-methods research process

from the local experience of flooding. Using this approach we developed an understanding of the level of knowledge about, and engagement with, the flood risk problem, as well as developing a trusting relationship between the researchers and the CFAG.

4.2.2 Adopting a participatory approach to developing new flood risk communications: the Corbridge Flood Research Group

The relationship developed between the researchers and the CFAG during Phase 1 was instrumental in developing the Corbridge Flood Research Group (CFRG), which was developed through Phase 2 of the research. The CFRG was a group loosely modelled on the Environmental Competency Group used by Lane et al. (2011). Similar to Lane et al. the CFRG was set apart from traditional focus or consultation groups by its focus on the practice of knowledge creation as a collaborative process and the integration of local 'non-experts' into a practice of flood management usually carried out far removed from the local scale.

The CFRG consisted of six, self-selected members of the wider CFAG who had personal experiences of (five members), or interest in (one member), flooding at Corbridge. One of the researchers (Rollason) also took an active role in the group as a member, as opposed to a more traditional role as facilitator or group leader. Local members of the group contributed their experiential knowledge of flooding and flood communication, whilst Rollason (as an academic specialist and former professional flood manager in industry) brought expert technical knowledge and experience. By blending these two perspectives, the group was able to consider both the CFRG's communication desires and the practicalities of what could be achieved.

CFRG meetings were framed specifically to explore flood risk communications. The group met three times; only the theme of the first, '*how flood risk is currently communicated?*' was predetermined. Subsequent meetings were driven by the group discussions and were predominantly unstructured, with participants determining what should be discussed and how. Meetings were audio–recorded, and field notes taken. After each meeting key discussion points were summarised, notes circulated to the group; all members thus participated in the iterative and ongoing development of the narrative being developed. Analysis of the material was undertaken throughout the process by adopting a flexible, mixed-method approach, situated within the principles of grounded theory (Knigge and Cope 2006; Charmaz 2011), for identifying and linking key areas of discussion. The discussions held with the group during CFRG1 and CFRG2 allowed Rollason to prepare a series of prototype interfaces for communication. The technical skills employed involved flood risk mapping using GIS software and running two-dimensional flood models to capture and present information. The prototypes were presented for group deliberation at CFRG3, with the group jointly choosing four concepts and then working together to produce a final, shared version which represented the agreed outputs from the group.

4.2.3 Testing the prototypes outside the CFRG

In the final stage of the research the prototypes were presented to a larger focus group consisting of eight members of CFAG (new to the research), Rollason and one original member of the CFRG. The design and purpose of the concepts were outlined, and the focus group discussed what they thought of the ideas, how they might be used, and any alternative ideas. The key aspects of this discussion were recorded during the focus group. No further amendment of the concepts was deemed necessary following discussions.

5 Current flood risk communications: Do current approaches meet users' needs?

5.1 Understanding local knowledge and experiences of flooding

The initial CFAG workshops and CFRG1 revealed that local participants had a wealth of experiential knowledge about flooding. Many also had an understanding of wider catchment processes developed through hobbies, such as fishing, or work. Despite this, few participants had expected the flooding to occur despite the receipt of an official flood warning (see Sect. 5.2), with many assuming that the recently completed flood defences would protect them, as one participant stated:

> To be honest I didn't really believe it, because we had such faith in the flood defences that I actually didn't think we'd flood (Participant GW44)

Based on this commonly held belief, several participants made the decision not to evacuate, even when contacted by the emergency services (Oliver 2016). That participants were surprised by the flooding, and unsure of how to react to it, demonstrates that flood communications had not developed the resilience of the Corbridge community to respond to flooding after the 2005 flood. These findings highlighted the need to examine in more detail how current flood risk communications were used by participants and how they might be redesigned to better develop resilience.

5.2 Reflections on current methods of flood risk communication

The CFRG members were familiar with the principle communications provided by the EA and several had used them before the 2015 flood. Table 3 summarises the group's attitudes towards the current flood communications, and these are expanded upon below.

Table 3 Summary of the CFRG perspectives on existing flood risk communications

Communication type	What the group thought about current approaches	What the group wanted from a future approach
Active communications • Live gauges • Flood warnings	- Useful but lacking in explanatory context and therefore difficult to interpret - A lack of future prediction makes it difficult for people to know when and how to respond to a potential flood	- Forecast water levels - Forecast of how serious a flood is likely to be - Water level information viewable at a catchment scale
Passive communications • All non-live flood maps	- Too simplistic to be of any use except when buying a house - Complex probabilistic language is difficult to interpret or place in context	- Detailed impacts on individual properties - Integration of active and passive communications - Communication of flood dynamics and timings rather than just extents to provide explanatory context

Members classified the approaches into 'passive' (the static, online flood maps) and 'active' communications (the live river level gauges and flood warnings) during the group discussion held during CFRG1

The CFRG felt that current approaches did not provide them with enough information to understand their flood risk or make an informed decision of what to do when they received a flood warning. In the case of the passive communications, the simple presentation of a flood risk extent, lacking any information on how floods occur, provided them with no information that they could actually use to understand what the stated flood risk meant. Participants stated they only used these maps for buying their homes or negotiating insurance; other than this participants thought that the maps told them nothing that they did not know already:

> For me, I know I'm in a high risk area so all it [the flood map] would tell me is what I know already (Participant GW44)

Some participants also expressed a lack of trust in how the maps had been produced, as one participant explained:

> Originally, when they did the first online extreme flood map they drew the lines through the centre of the church […], and I said "if it's getting to that level, it's coming down my chimney" (Participant AK97)

The church at Corbridge sits approximately 16 m above the floodplain. The group member still linked this experience and his distrust of those original maps to the current flood maps which appear superficially the same. The advancements in modelling and data since the production of the early maps are not evident in the way the maps are communicated, and information on how they are actually produced is not publicly available.

Participants were much more engaged with the active communications, particularly the online availability of real-time river levels. Several CFRG members noted that they watched gauges upstream of Corbridge to try and judge how river levels might change at Corbridge in the near future. However, all participants expressed frustration with the lack of forecast river levels, which did not allow them to judge when flooding might occur, or how severe flooding of their homes might be in comparison with past events. This was a particular problem when participants received flood alerts, preliminary warnings that flooding *might* occur in the near future. These alerts, issued some time before formal flood warnings, are intended to prompt people to begin monitoring local river levels and prepare to take protective action. However, participants felt that the lack of forecast information left them unable to judge what to do and when.

Fundamentally, participants felt that the information they were being provided currently told them when to act, but did not provide them with enough information to judge what it was feasible for them to do, or to what extent they should take action. As one participant noted regarding the 2015 floods:

> When we put things up high, not thinking that when the river comes over the water was going to be so high it would upend all those things, so everything I put up high to save we lost (Participant GW44)

5.3 What information do users want in flood communications?

CFRG2 focused on the information that people actually wanted from flood communications to allow them to understand their risk and take action, setting aside for the moment the practicalities of whether or not such information could be provided. The discussions reflected their initial criticisms of existing communications, focusing particularly on understanding the severity of the risk, and therefore what degree of action they could and should take (Table 3). Ultimately, group members wanted flood levels to be forecast, and a specific linkage between what these flood levels meant for their properties and what they could do in response, for example how high they needed to lift valuables:

> What you need is the starkest information, […] this level [in the river] means that level [on the floodplain], means this amount of water in your house (Participant MJ33)

> I want to know […] if it's that high, I'm going to do this, if it's going to be like 2005, I need to do that, because that was much less flooding (Participant GW44)

These discussions encompassed both passive and active communications, with participants generally agreeing that active communications, such as the river level graphs, should be more specifically linked to the passive communications, which could provide more in-depth and detailed information on property-level impacts.

Some group members were concerned that providing more complex information would be confusing and potentially undermine responses to flooding. As a result, the group discussed how it was necessary to communicate flooding dynamics, for example how, when, and where flooding might occur, in order to be able to effectively interpret local flood risk. Participants referred to this type of information as contextual information, examples of which included where and when flood defences might be over-topped and how flood water might flow across the floodplain in order to flood their properties. This potentially reflects the relatively complex dynamics of the 2015 flood, where the principle areas of defence over-topping were out of sight of participants properties, and therefore flooding occurred from an unexpected direction.

6 Working together on new approaches to communicating flood risk

Between CFRG2 and CFRG3 a series of draft prototypes of alternative passive and active flood risk communications were developed. Six prototypes were originally produced, exploring different types of information that could be communicated and different ways of communicating it (Table 4). Although the CFRG2 discussions had considered participants' information aspirations without considering the practicalities of implementing them, the group felt that it was important, in producing the prototypes, to consider how these ideas might be implemented in practice. Thus, where possible, proposals draw inspiration from existing examples of flood risk communications in other countries, proposed methods drawn from the literature, or examples of communications drawn from other fields (Table 4).

The prototypes were the focus of CFRG3. From the suite of initial concepts developed, the group considered four to be particularly useful (Fig. 4). These four were considered by

Table 4 Summary of the initial prototypes for new passive and active flood communications produced between CFRG2 and CFRG3 to communicate flood risk in different ways

Mock-up		Focus of the approach	Sources of inspiration
1a	Catchment-wide gauge map	Shows the status of river gauges across the Tyne catchment indicating current status and rate of change of status where applicable	Fishpal website (Fishpal.com)
1b	Catchment-wide gauge map, zoomed in example	Shows current flood warnings and status of gauges in a zoomed in fashion	Existing flood communications maps and researcher experience
2	Gauge graph examples dashboard	Shows multiple gauges in a single 'dashboard' Gauges display different options: 1. Current approach 2. Current approach with historical hydrograph overlay 3. Current approach with future water level prediction 4. Current approach with both (2) and (3)	Proposed alternative approaches were based on 1. Current display options 2. With research interpretation of CFRG suggestions 3. Proposed prediction options from Leedal et al. (2012)
3a	Flood impacts explorer—flood depths	Shows modelled flood depths from a previous flood event (2016)	Existing flood depth maps and researcher experience
3b	Flood impacts explorer—flood pathways	Shows modelled flood depths and explanatory context of key flood pathways and timings. Shows linked flood hydrograph indicating water levels at which key mechanisms become active	Flood depth maps and from researcher interpretation of key information requested by the CFRG members
3c	Flood impacts explorer—historical frequency	Shows modelled flood depths with indication of historical frequency of flooding events of given magnitude	USGS flood inundation mapper 'historical flooding' information (United States Geological Survey 2016)
3d	Flood levels explorer—potential water levels	Shows user variable water level indicator, demonstrating potential flood extent and depth at different gauged water levels. Could be based on either local assessment of a digital elevation model, or a model outputs library (for example, see Hogan Carr et al. 2016)	USGS flood inundation mapper 'Flood Inundation Map Library' (United States Geological Survey 2016; Hogan Carr et al. 2016)

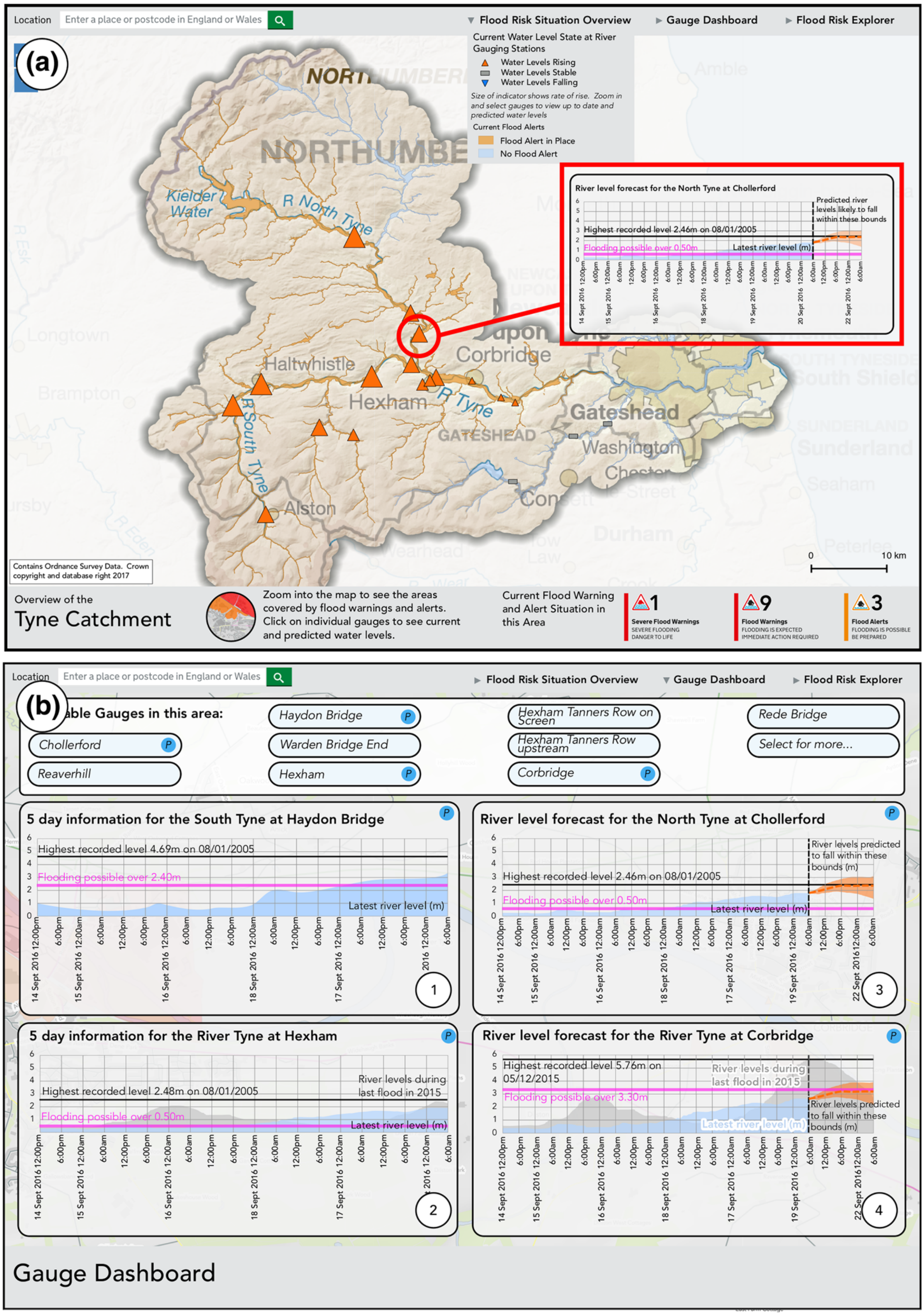


Fig. 4 Flood risk communication concepts adopted by the CFRG (concept numbers relate to details in Table 4). **a** CFRG Concept 1a showing the catchment-wide overview of the river gauging station status. **b** CFRG Concept 2 showing a proposed gauge dashboard allowing users to 'pin' multiple gauges of their choice into a single place for rapid review of how river levels upstream are responding to rainfall. **c** CFRG Concept 3b outlining a detailed assessment of historical flood dynamics (in this case the December 2016 flood event). **d** CFRG Concept 3d shows a user-selected water level from the Corbridge gauge and displays the corresponding extent and depth of flooding based on simple water level interpolation

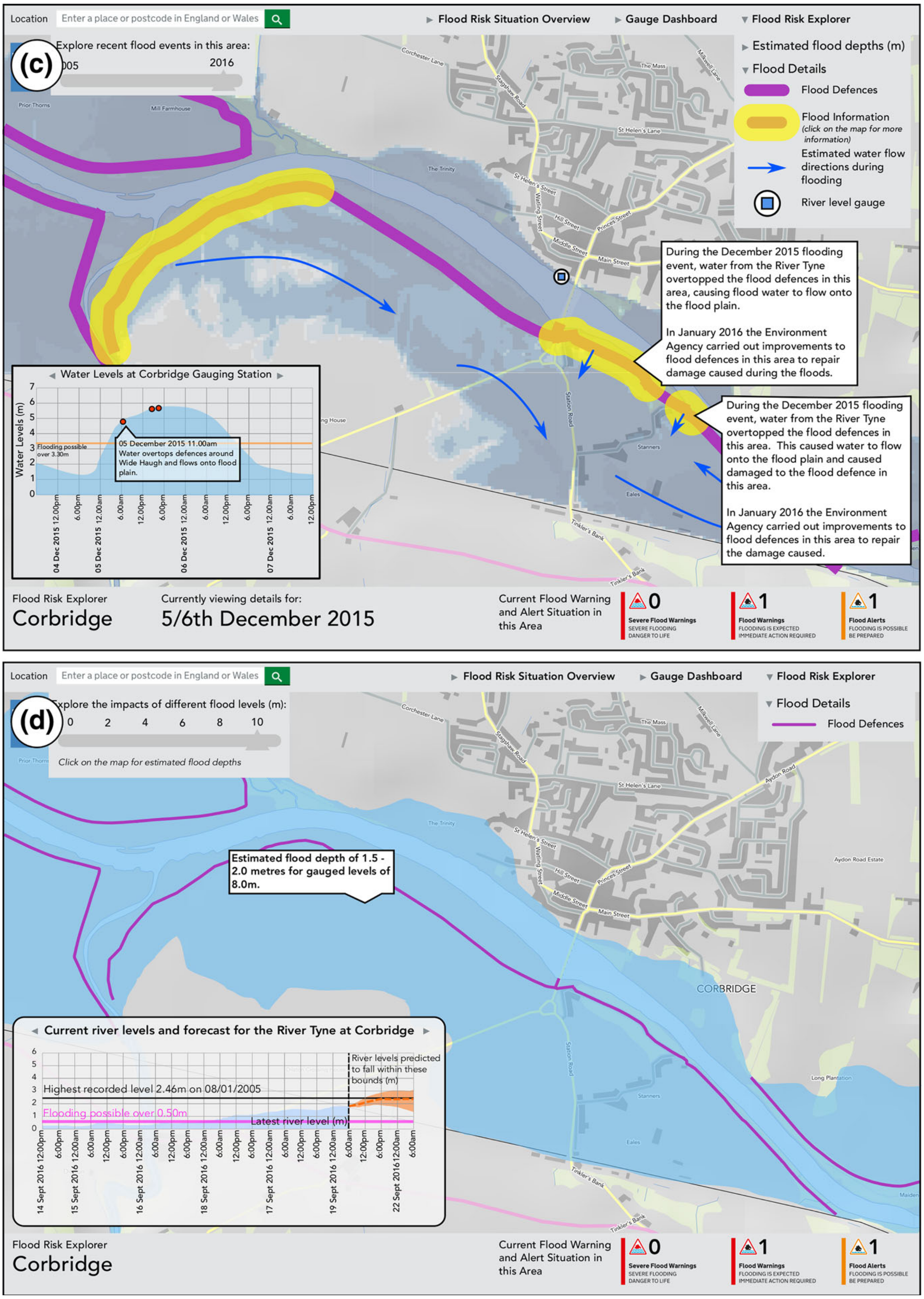


Fig. 4 continued

the local participants to give them the information they felt they needed to understand the risk of flooding, but also to make informed decisions about what action to take, and when, for future floods. These four prototypes were further developed by the group during and after CFRG3, and those shown in Fig. 4 represent the final, agreed outputs from the group.

The four prototypes adopted by the group reflect the CFRG's two core desires:

1. to be able to take responsibility for effectively monitoring their flood risk and judge, through forecast information, how significant any flooding might be (Fig. 4a, b).
2. to have a detailed understanding of how flooding might occur based on a knowledge of past flooding dynamics (Fig. 4c) and to be able to link forecast flooding information with the potential impacts on their own properties, allowing them to judge what action they could take in response.

Figure 4a shows the catchment-wide overview of the river gauging station status, enabling users to quickly assess how the catchment is responding to rainfall. This prototype map is linked specifically to individual gauge records allowing users to select and explore specific sites in more detail. Inspired by the online angling tool 'Fishpal' (Fishpal.com) used by one of the CFRG participants, the group members felt this tool allowed them to easily monitor catchment-scale river response, using their knowledge of how rainfall in different areas of the catchment translated into flood risk at Corbridge.

Figure 4b outlines a prototype gauge dashboard which allows users to 'pin' multiple gauges of their choice into a single place for rapid review of how river levels upstream are responding to rainfall. This prototype answers group members annoyance with only being able to view one gauge at a time using the current system. This prototype also reflects different options for how gauged levels should be displayed, which were also discussed by the CFRG: (1) current approach adopted by the Environment Agency; (2) current approach with an overlay comparing current levels with a historical hydrograph; (3) current approach including predicted future water levels based on the method proposed by Leedal et al. (2012); or (4) current approach with both (2) and (3). CFRG participants felt that forecast water levels (as in 3) allowed them to plan protective actions in advance of flooding occurring by anticipating when they would need to take certain actions, whilst historical comparisons (such as that shown in 2) allowed them to contextualise the significance of predictions and therefore judge what level of protective action was necessary.

Figure 4c presents a detailed assessment of historical flood dynamics (in this case the December 2015 flood event). In this prototype users would be able to select different elements to be provided with a detailed account of how flooding occurred, and what action might have been taken in response. The hydrograph allows users to identify water levels at which different flooding mechanisms begin to operate. CFRG members felt this map developed their understanding of how flooding occurred and when, allowing them to understand the significance of local gauged river levels.

Figure 4d shows the simulated extent and depth of potential flooding based on a user-selected water level for the Corbridge gauge. This prototype was inspired by the United States Geological Survey 'Flood Inundation Map Library' (United States Geological Survey 2016). Current and predicted water levels at Corbridge are displayed on the gauge display to allow users to link current and predicted water levels with their evaluation of potential impacts. CFRG participants felt this simple linkage between river levels and potential floodplain impacts was important for correctly interpreting what forecast river levels might mean and for demonstrating what degree of protective action was needed in different situations.

7 Scaling up: testing the prototypes with the wider Corbridge Flood Action Group

The four updated prototypes were presented to the wider CFAG at a group meeting and also at a smaller focus group. The prototypes were well received by the focus group (Table 5), with the underlying themes of understanding flood dynamics, flood impacts and future prediction being reflected in the discussions. All participants saw the potential for the active communications to enable them to take action to reduce the impact of future floods.

The prototype in Fig. 4c provoked a different response to that of the CFRG. The focus group members thought that this map was not for them to use in preparing for flooding, but instead was as a tool for them to use to engage more effectively with the EA about ongoing FRM on a more even information footing:

> I think that information is important for us to see, so that we can have intelligent conversations with the Environment Agency (focus group participant)

Instead, to prepare for a flood in the near future, the focus group participants preferred the simple water level model shown in Fig. 4d.

This discussion highlights the complex interactions between individual users and the different approaches to communicating flood risk and the difficulties of presenting only a small variety of information in order to represent a complex and dynamic threat such as flooding.

Table 5 Responses to the CFRG mock-ups from the Corbridge Flood Action Group Focus Group (CFRG mock-up numbers refer to Table 5)

CFRG mock-up	Summary of Flood Group Focus Group responses
1a Gauges overview	• Very useful for understanding the overall view of the catchment • Can look at the whole river all at once and can be used to understand how large a flood might be • Would need to be able to understand what the information meant for flood impacts at Corbridge • Would like to see predictors of water level increases on the overview map
2 Gauge dashboard	• Predicted and historical information both useful in indicating potential magnitude and also providing context for understanding what levels mean • Do not consider (4) to be too complex • Would like an indication of key trigger points, for example level at which defence over-topping begins • Uncertainty very important in predictions of water levels to avoid users minimising future warnings
3b Flood explorer, pathways and timings	• Provides a vivid contextual understanding of what occurred during previous floods • Not necessary or interpreting current or future events, gauged, real-time information much better for this • Much more useful for engaging with the EA regarding flood management activities
3d Flood explorer, user-simulated flood depths	• Very useful for understanding flood impacts and allowing users to link gauged information with potential flood depths • More useful than the historical pathways and timings idea

8 Discussion

In this section we bring together the experience of the CFRG experiment with theories of risk communication. We argue that participation such as that demonstrated by the CFRG must play a role in developing future flood communications, especially in light of the shift from flood defence to flood management and the resulting distribution of FRM responsibilities onto those at risk (Butler and Pidgeon 2011). Such involvement will enable responsible agencies to better communicate flood risk in new ways, empowering those at risk to apply their local knowledge and experience to improve their resilience in the face of flood events.

8.1 Implications for current flood risk communications

The research undertaken has shown that there are severe limitations to current flood risk communication approaches which prioritise simple threat messages. The PMT model (Rogers 1975) can be used to analyse the responses of the CFRG to the existing flood communications and their desire for alternative approaches, focusing particularly on the ideas of the threat and coping appraisal (Grothmann and Reusswig 2006). The CFRG saw no useful information in the existing passive maps, which suggests that this approach does not support the development of threat appraisal. The lack of information on flood dynamics also provides no basis on which users can judge for themselves how communicated risk information might translate into an impact on their own property. In this context, threat appraisal is reliant on previous experiences, whether personal or vicarious. In the Corbridge context this wholly underestimated the threat, resulting in a non-protective response based on 'wishful thinking' regarding the recently completed flood defence works. Hopkins and Warburton (2015) refer to this paradox as the 'prison of experience', in which infrequent or unrepresentative events imprint themselves into subjective knowledge as representative experiences to be drawn on in the future. CFRG participants' desire for detailed information on past local flooding characteristics or the simple flood depth simulator can be seen as an attempt to place their experiences in a wider context, breaking out of the prison of experience and establishing a more holistic understanding.

Both the passive and active communications assessments also suggest a failure of current approaches to establish a meaningful coping appraisal, particularly in relation to the judgement of how much time participants in this study had to react and what degree of action they should, or could, take. Several participants expressed surprise at the prototype flood map showing flood dynamics, which highlighted over-topping of upstream defences approximately 4 h prior to property flooding occurring. These participants had no understanding from the current flood maps (which do not show information such as areas of potential over-topping) that flooding might either be inevitable or occurring, or that they potentially had several hours in which to prepare or act. Neither were participants able to accurately judge the degree to which they should prepare based on the live gauged information, since this online information does not currently offer information on predicted water levels. This led to negative coping appraisals and the adoption of non-protective behaviours, where participants either ignored what might be happening or took ineffective action. In this context, the Group's desire to see whole-catchment-scale information, which incorporates future predictions, can be seen as building not just their personal appraisal of the threat, but also their coping appraisal. Understanding the threat allows them to feel in control of their own flood risk situation and to make their own decisions, rather than reacting blindly to flood warnings; a situation that participants said left them very stressed and uncertain.

8.2 Future flood risk communications: participation as a vehicle for developing resilience through flood literacy

Viewed in the context of the PMT, current flood risk communications could therefore be judged to be counterproductive; they attempt to provoke a heightened perception of flood risk, without providing the information required by users to establish strong, positive threat *and* coping appraisals. Without developing coping appraisals, users adopt the kinds of non-protective behaviours proposed by Bubeck et al. (2012), ignoring, rejecting or misinterpreting official risk information to make them *feel* more secure in the face of extreme uncertainty (Harries 2008). These behaviours reduce community resilience by increasing the shock of events when they occur unexpectedly or do not match individuals previous experiences; increase individual hazard through refusals to evacuate; or foster learned helplessness when believed protective behaviours fail or have no effect.

To encourage positive threat and coping appraisals future flood communications need to move away from the simplistic flood threat messages that are currently cascaded to people at risk. Instead, and as the four prototypes created here demonstrate, communications should provide more detailed, holistic hazard information. This type of information, rather than relying on raising risk perception alone, seeks to develop a local ‘flood literacy’ by fostering local knowledge about flooding. Flood literacy repositions those at risk as active agents in managing local flood risk, able to make their own judgements and decisions on risk and protective behaviour, rather relying on expert knowledge (Willis et al. 2011). By empowering people in this way, flood literacy develops local resilience in a way in which simple, threat-based communications cannot: it provides at-risk individuals and communities with the information necessary to (1) assess their personal level of risk and how they might be affected, (2) determine when a flood might be about to occur and how it might affect them, and (3) determine appropriate actions by which they might mitigate potential flood impacts.

To encourage effective flood literacy through improved flood risk communications, there is a need to re-establish resilience as a process grounded in relationships, social learning and dialogue (Twigger-Ross et al. 2011, 2014; Benson et al. 2016), rather than ‘hard’ infrastructure or property (McBain et al. 2010). Participatory approaches offer a potential avenue through which the reinvigoration of resilience in this fashion might occur. The results of our research demonstrate the importance of working together with end-users in developing new solutions to flood risk problems, similar to the findings of previous participatory research (Landström et al. 2011; Lane et al. 2011; Whitman et al. 2015; Bracken et al. 2016). The practices of participatory working help to unify local and official perspectives on flood risk and develop local capacity to understand and take action (Pain 2004) in ways that established approaches to communication have been shown not to be able to achieve.

9 Conclusions

The last three decades have seen rapid changes in our approaches to addressing flood risk, and a professional acceptance that flooding cannot be prevented and must instead be managed. Societal resilience to floods has emerged as a key pillar of this new approach to ‘living with floods’. Changes in policy have increasingly focused on the resilience of critical infrastructure, and developing community resilience has increasingly been undertaken through an educational model of risk communication. However, research suggests that this approach is failing to develop individual and community capacities for understanding and responding to floods in a resilient manner.

The research presented here has demonstrated the application of participatory approaches to exploring the linkage between flood risk communication, individual behaviour and generating resilience. We have worked together with a competency group drawn from a flood-affected community to understand how they use and interpret current flood risk communications, what information is important to them in understanding and responding to floods in a resilient manner and how could information be better communicated. Our conclusions are as follows:

1. Current approaches to flood risk communications fail to meet user needs in understanding flood risk or allowing personal judgements of how and when to act. Through a reliance on communicating simple, threat-based messages rather than developing in-depth understanding, current communications heighten threat appraisal, but diminish coping appraisal. This promotes non-protective behaviours, either through wishful thinking and over-reliance on management organisations, or through denial and learned helplessness.
2. Users desire a greater range of information about floods, including locally specific information on flood dynamics, which would allow them to understand their personal flood risk situation and how floods will affect them. Delivering this information is vital to enable those at risk to judge what protective actions they can take, and when they should take action. Our results demonstrate that users desire forecast information beyond what is provided currently. Without forecasts of river levels or flood extents, users are unable to judge the potential severity of future flooding, which means they are reluctant or unwilling to take action blindly.
3. There are a great variety of different perspectives on how flood risk should be communicated and the purpose of these communications, even within a small area. The complexity of the risk message–behaviour interface means that one message cannot be tailored to all perspectives. We propose a communications model which is instead focused on the development of ‘flood literacy’, where communities and individuals are empowered to develop their own knowledge about local flood risk and how they can act to manage it.
4. Flood literacy can reinvigorate flood communications as a tool for developing flood resilience by establishing flood communications as a two-way dialogue focused on the development of shared, locally grounded knowledge. Participatory working approaches represent a vehicle through which communications and resilience can be linked. Resilience and participation are both grounded in the principles of trust, the development of relationships, and the co-production of knowledge and solutions. Participation therefore has the potential to offer a solution, re-imagine our approaches to communication, integrate alternative perspectives and place ‘knowledge consumers’ at the heart of the process.

5. We propose four co-produced prototype user interfaces which can deliver the information needed to help those at risk develop flood literacy.

The challenge of quantifying how new and innovative modes of knowledge creation, communications and relationship-building can provide valuable opportunities for bettering flood risk management remains. However, the approaches described here have important implications for how we communicate flood risk and how we work alongside those living with risk to develop more flood-resilient communities.

Acknowledgements The authors would like to thank the members of the Corbridge Flood Action Group for their participation in this study, and particularly those who gave of their time to be involved in the Flood Research Group. We would also like to thank the two anonymous reviewers for their comments which helped shape the final manuscript.

Funding This work was supported by the Natural Environments Research Council [Grant Number NE/L002590/1]. Data presented in this manuscript can be obtained by contacting ER.

References

Archer DR, Leesch F, Harwood K (2007a) Assessment of severity of the extreme River Tyne flood in January 2005 using gauged and historical information. Hydrol Sci J 52:992–1003. https://doi.org/10.1623/hysj.52.5.992

Archer DR, Leesch F, Harwood K (2007b) Learning from the extreme River Tyne flood in January 2005. Water Environ J 21:133–141. https://doi.org/10.1111/j.1747-6593.2006.00058.x

Benson D, Lorenzoni I, Cook H (2016) Evaluating social learning in England flood risk management: an 'individual-community interaction' perspective. Environ Sci Policy 55:326–334. https://doi.org/10.1016/j.envsci.2015.05.013

Bracken LJ, Oughton EA, Donaldson A et al (2016) Flood risk management, an approach to managing cross-border hazards. Nat Hazards. https://doi.org/10.1007/s11069-016-2284-2

Bubeck P, Botzen WJW, Aerts JCJH (2012) A review of risk perceptions and other factors that influence flood mitigation behavior: review of flood risk perceptions. Risk Anal 32:1481–1495. https://doi.org/10.1111/j.1539-6924.2011.01783.x

Bucchi M, Neresini F (2008) Science and public participation. In: Hackett EJ, Amsterdamska O, Lynch M, Wajcman J (eds) The handbook of science and technology studies, 3rd edn. MIT Press, Cambridge, pp 449–472 **(Published in cooperation with the Society for the Social Studies of Science)**

Burningham K, Fielding J, Thrush D (2008) 'It'll never happen to me': understanding public awareness of local flood risk. Disasters 32:216–238. https://doi.org/10.1111/j.1467-7717.2007.01036.x

Burns WJ, Slovic P (2012) Risk perception and behaviors: anticipating and responding to crises: risk perception and behaviors. Risk Anal 32:579–582. https://doi.org/10.1111/j.1539-6924.2012.01791.x

Butler C, Pidgeon N (2011) From 'flood Defence' to 'flood risk management': exploring governance, responsibility, and blame. Environ Plan C Gov Policy 29:533–547. https://doi.org/10.1068/c09181j

Callon M (1999) The role of lay people in the production and dissemination of scientific knowledge. Sci Technol Soc 4:81–94. https://doi.org/10.1177/097172189900400106

Charmaz K (2011) A constructivist grounded theory analysis of losing and regaining a valued self. In: Wertz FJ (ed) Five ways of doing qualitative analysis: phenomenological psychology, grounded theory, discourse analysis, narrative research, and intuitive inquiry. Guilford Press, New York, pp 165–204

Chatterton J, Viavattene C, Morris J et al (2010) The costs of the summer 2007 floods in England. Environment Agency, Bristol

Davies R (2015) Two-thirds of UK Households fail to check flood risk levels. In: FloodList. http://floodlist.com/protection/two-thirds-uk-households-fail-to-check-flood-risk. Accessed 18 June 2015

de Moel H, van Alphen J, Aerts JCJH (2009) Flood maps in Europe—methods, availability and use. Nat Hazards Earth Syst Sci 9:289–301. https://doi.org/10.5194/nhess-9-289-2009

Demeritt D, Norbert S (2014) Models of best practice in flood risk communication and management. Environ Hazards 13:313–328. https://doi.org/10.1080/17477891.20l4.924897
Environment Agency (2009) Flooding in England: a national assessment of flood risk
Environment Agency (2010) Flood and coastal risk management risk mapping strategy 2010–2015
Environment Agency (2011) National flood and coastal erosion risk management strategy for England. https://www.gov.uk/government/publications/national-flood-and-coastal-erosion-risk-management-strategy-for-england. Accessed 13 Oct 2014
Environment Agency (2012) Recommendations for flood mapping in England and Wales: findings from the RISK MAP ERA-NET CRUE. Environment Agency, Bristol
Environment Agency (2016) Impact report winter flooding 2015–16-Northumberland, Durham and Tees Area
Environment, Food and Rural Affairs Select Committee (2016) Future flood prevention. In: www.parliament.uk. http://www.publications.parliament.uk/pa/cm201617/cmselect/cmenvfru/115/11502.htm. Accessed 15 Nov 2016
European Parliament and the Council (2007) Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks
EXCIMAP (2007a) Handbook on good practices for flood mapping in Europe
EXCIMAP (2007b) Atlas of flood maps
Fishpal.com FishPal.com. http://www.fishpal.com/. Accessed 12 Apr 2017
Fielding J, Burningham K, Thrush D, Catt R (2007) Public response to flood warning. Environment Agency, Bristol
Fischhoff B, Bostrom A, Quadrel MJ (1993) Risk perception and communication. Annu Rev Public Health 14:183–203. https://doi.org/10.1146/annurev.pu.14.050193.001151
Fisher H (2015) Public dialogues on flood risk communication. Environment Agency, Bristol
Flood Information Service Flood Information Service (2017) https://flood-warning-information.service.gov.uk/. Accessed 12 Apr 2017
Gilissen HK, Alexander M, Matczak P et al (2016) A framework for evaluating the effectiveness of flood emergency management systems in Europe. Ecol Soc. https://doi.org/10.5751/ES-08723-210427
Grothmann T, Reusswig F (2006) People at risk of flooding: Why some residents take precautionary action while others do not. Nat Hazards 38:101–120. https://doi.org/10.1007/s11069-005-8604-6
Hagemeier-Klose M, Wagner K (2009) Evaluation of flood hazard maps in print and web mapping services as information tools in flood risk communication. Nat Hazards Earth Syst Sci 9:563–574. https://doi.org/10.5194/nhess-9-563-2009
Harries T (2008) Feeling secure or being secure? Why it can seem better not to protect yourself against a natural hazard. Health Risk Soc 10:479–490. https://doi.org/10.1080/13698570802381162
Hogan Carr R, Montz B, Maxfield K et al (2016) Effectively communicating risk and uncertainty to the public: assessing the national weather service's flood forecast and warning tools. Bull Am Meteorol Soc 97:1649–1665. https://doi.org/10.1175/BAMS-D-14-00248.1
Hopkins J, Warburton J (2015) Local perception of infrequent, extreme upland flash flooding: Prisoners of experience? Disasters 39:546–569. https://doi.org/10.1111/disa.12120
Kindon SL, Pain R, Kesby M (eds) (2007) Participatory action research approaches and methods: connecting people, participation and place. Routledge, New York
Knigge L, Cope M (2006) Grounded visualization: integrating the analysis of qualitative and quantitative data through grounded theory and visualization. Environ Plan A 38:2021–2037. https://doi.org/10.1068/a37327
Lamond JE, Joseph RD, Proverbs DG (2015) An exploration of factors affecting the long term psychological impact and deterioration of mental health in flooded households. Environ Res 140:325–334. https://doi.org/10.1016/j.envres.2015.04.008
Landström C, Whatmore SJ, Lane SN et al (2011) Coproducing flood risk knowledge: redistributing expertise in critical 'participatory modelling'. Environ Plan A 43:1617–1633. https://doi.org/10.1068/a43482
Lane SN (2012) Ethical risk management, but without risk communication? In: Kearnes M, Klauser FR, Lane SN (eds) Critical risk research practices, politics, and ethics. Wiley, Hoboken
Lane SN, Odoni N, Landström C et al (2011) Doing flood risk science differently: an experiment in radical scientific method. Trans Inst Br Geogr 36:15–36. https://doi.org/10.1111/j.1475-5661.2010.00410.x
Leedal D, Weerts AH, Smith PJ, Beven KJ (2012) A data based mechanistic real-time flood forecasting module for NFFS FEWS. Hydrol Earth Syst Sci Discuss 9:7271–7296. https://doi.org/10.5194/hessd-9-7271-2012
Marsh T, Kirby C, Muchan K et al (2016) The winter floods of 2015/2016 in the UK—a review. Centre for Ecology and Hydrology, Wallingford

McBain W [Main author], Wilkes D, Retter M, Construction Industry Research and Information Association (2010) Flood resilience and resistance for critical infrastructure. CIRIA, London

Mees H, Crabbé A, Alexander M et al (2016) Coproducing flood risk management through citizen involvement: insights from cross-country comparison in Europe. Ecol Soc. https://doi.org/10.5751/ES-08500-210307

Meyer V, Kuhlicke C, Luther J et al (2012) Recommendations for the user-specific enhancement of flood maps. Nat Hazards Earth Syst Sci 12:1701–1716. https://doi.org/10.5194/nhess-12-1701-2012

Milojevic A, Armstrong B, Wilkinson P (2017) Mental health impacts of flooding: a controlled interrupted time series analysis of prescribing data in England. J Epidemiol Community Health 71:970–973. https://doi.org/10.1136/jech-2017-208899

Munro A, Kovats RS, Rubin GJ et al (2017) Effect of evacuation and displacement on the association between flooding and mental health outcomes: a cross-sectional analysis of UK survey data. Lancet Planet Health 1:e134–e141. https://doi.org/10.1016/S2542-5196(17)30047-5

O'Sullivan JJ, Bradford RA, Bonaiuto M et al (2012) Enhancing flood resilience through improved risk communications. Nat Hazards Earth Syst Sci 12:2271–2282. https://doi.org/10.5194/nhess-12-2271-2012

Oliver K (2016) Flooding: a resident's view of Saturday 5th December. Corbridge Matters

Pain R (2004) Social geography: participatory research. Prog Hum Geogr 28:652–663

Paton D, Johnston D (2001) Disasters and communities: vulnerability, resilience and preparedness. Disaster Prev Manag Int J 10:270–277. https://doi.org/10.1108/EUM0000000005930

Paton D, Johnston DM (2006) Disaster resilience: an integrated approach. Charles C Thomas Publisher, New York

Rogers RW (1975) The protection motivation theory of fear appeals and attitude change. J Psychol 91:93–114

Slovic P, Kunreuther H, White GF (1974) Decision processes, rationality and adjustment to natural hazards. Earthscan Publications, London

Terpstra T (2011) Emotions, trust, and perceived risk: affective and cognitive routes to flood preparedness behavior: affective and cognitive routes to flood preparedness behavior. Risk Anal 31:1658–1675. https://doi.org/10.1111/j.1539-6924.2011.01616.x

Terpstra T, Gutteling JM (2008) Households' perceived responsibilities in flood risk management in the Netherlands. Int J Water Resour Dev 24:555–565. https://doi.org/10.1080/07900620801923385

Twigger-Ross C, Coates T, Orr P et al (2011) Community resilience research: final report on theoretical research and analysis of case studies report to the Cabinet Office and Defence Science and Technology Laboratory. Collingwood Environmental Planning Ltd, London

Twigger-Ross C, Kashefi E, Weldon S et al (2014) Flood resilience community pathfinder evaluation rapid evidence assessment. Defra, London

United States Geological Survey (2016) Flood inundation mapping (FIM) program. https://water.usgs.gov/osw/flood_inundation/. Accessed 12 Apr 2017

Van Alphen J, Martini F, Loat R et al (2009) Flood risk mapping in Europe, experiences and best practices. J Flood Risk Manag 2:285–292. https://doi.org/10.1111/j.1753-318X.2009.01045.x

Wachinger G, Renn O, Begg C, Kuhlicke C (2013) The risk perception paradox-implications for governance and communication of natural hazards: the risk perception paradox. Risk Anal 33:1049–1065. https://doi.org/10.1111/j.1539-6924.2012.01942.x

Waite TD, Chaintarli K, Beck CR et al (2017) The English national cohort study of flooding and health: cross-sectional analysis of mental health outcomes at year one. BMC Public Health 17:129. https://doi.org/10.1186/s12889-016-4000-2

Whitman GP, Pain R, Milledge DG (2015) Going with the flow? Using participatory action research in physical geography. Prog Phys Geogr. https://doi.org/10.1177/0309133315589707

Willis KF, Natalier K, Revie M (2011) Understanding risk, choice and amenity in an urban area at risk of flooding. Hous Stud 26:225–239. https://doi.org/10.1080/02673037.2011.549215

Bibliography

Abdulkareem, M., Elkadi, H., Bneane, M., 2018. From engineering to evolutionary, an overarching approach in identifying the resilience of urban design to flood. Int. J. Disaster Risk Reduct. https://doi.org/10.1016/j.ijdrr.2018.02.009

Adger, W.N., 2000. Social and ecological resilience: are they related? Prog. Hum. Geogr. 24, 347–364. https://doi.org/10.1191/030913200701540465

Afzalan, N., Sanchez, T.W., Evans-Cowley, J., 2017. Creating smarter cities: Considerations for selecting online participatory tools. Cities 67, 21–30. https://doi.org/10.1016/j.cities.2017.04.002

Akkar, S., Azak, T., Çan, T., Çeken, U., Demircioğlu Tümsa, M.B., Duman, T.Y., Erdik, M., Ergintav, S., Kadirioğlu, F.T., Kalafat, D., Kale, Ö., Kartal, R.F., Kekovalı, K., Kılıç, T., Özalp, S., Altuncu Poyraz, S., Şeşetyan, K., Tekin, S., Yakut, A., Yılmaz, M.T., Yücemen, M.S., Zülfikar, Ö., 2018. Evolution of seismic hazard maps in Turkey. Bull. Earthq. Eng. 16, 3197–3228. https://doi.org/10.1007/s10518-018-0349-1

Alexander, M., Priest, S., Penning-Rowsell, E.C., 2017. The risk of ill-informed reform: The future for English flood risk management. Area 50, 426–429. https://doi.org/10.1111/area.12393

Allen, W., Fenemor, A., Kilvington, M., Harmsworth, G., Young, R., Deans, N., Horn, C., Phillips, C., Montes de Oca, O., Ataria, J., Smith, R., 2011. Building collaboration and learning in integrated catchment management: the importance of social process and multiple engagement approaches. N. Z. J. Mar. Freshw. Res. 45, 525–539. https://doi.org/10.1080/00288330.2011.592197

Altenau, E.H., Pavelsky, T.M., Bates, P.D., Neal, J.C., 2017. The effects of spatial resolution and dimensionality on modeling regional-scale hydraulics in a multichannel river. Water Resour. Res. 53, 1683–1701. https://doi.org/10.1002/2016WR019396

Altschuler, D., Corrales, J., 2012. The Spillover Effects of Participatory Governance: Evidence From Community-Managed Schools in Honduras and Guatemala. Comp. Polit. Stud. 45, 636–666. https://doi.org/10.1177/0010414011427133

Archer, D.R., Leesch, F., Harwood, K., 2007a. Assessment of severity of the extreme River Tyne flood in January 2005 using gauged and historical information. Hydrol. Sci. J. 52, 992–1003. https://doi.org/10.1623/hysj.52.5.992

Archer, D.R., Leesch, F., Harwood, K., 2007b. Learning from the extreme River Tyne flood in January 2005. Water Environ. J. 21, 133–141. https://doi.org/10.1111/j.1747-6593.2006.00058.x

Arnstein, S.R., 1969. A Ladder Of Citizen Participation. J. Am. Inst. Plann. 35, 216–224. https://doi.org/10.1080/01944366908977225

Atkinson, P., Hammersley, M., 1994. Ethnography and participant observation., in: Handbook of Qualitative Research. Sage Publications, Inc, Thousand Oaks, CA, US, pp. 248–261.

Bahadur, A., Ibrahim, M., Tanner, T., 2010. The resilience rennaissance? Unpacking of resilience for tackling climate change and disasters Strengthening Climate Resilience Discussion Paper 1.

Baldock, D., Farmer, A., Nesbit, M., 2016. Brexit – the Implications for UK Environmental Policy and Regulation (A special independent report commissioned by the all party parliamentary environment group). All - Party Parliamentary Environment Group, London.

Ballweber, J.A., 2006. A Comparison of IWRM Frameworks: The United States and South Africa. J. Contemp. Water Res. Educ. 135, 74–79. https://doi.org/10.1111/j.1936-704X.2006.mp135001009.x

Banerjee, A., Duflo, E., Imbert, C., Mathew, S., Pande, R., 2016. E-governance, Accountability, and Leakage in Public Programs: Experimental Evidence from a Financial Management Reform in India (Working Paper No. 22803). National Bureau of Economic Research. https://doi.org/10.3386/w22803

Barker, L., Hannaford, J., Parry, S., 2016. Briefing Note: Severity of the December 2015 floods -- preliminary analysis [WWW Document]. Cent. Ecol. Hydrol. URL http://www.ceh.ac.uk/news-and-media/blogs/briefing-note-severity-december-2015-floods-preliminary-analysis (accessed 11.15.16).

Baruch, A., May, A., Yu, D., 2016. The motivations, enablers and barriers for voluntary participation in an online crowdsourcing platform. Comput. Hum. Behav. 64, 923–931. https://doi.org/10.1016/j.chb.2016.07.039

Bates, P.D., De Roo, A.P.J., 2000. A simple raster-based model for flood inundation simulation. J. Hydrol. 236, 54–77. https://doi.org/10.1016/S0022-1694(00)00278-X

Bates, P.D., Horritt, M.S., Fewtrell, T.J., 2010. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. J. Hydrol. 387, 33–45. https://doi.org/10.1016/j.jhydrol.2010.03.027

Bellamy, J., Ross, H., Ewing, S., Meppem, T., 2002. Integrated Catchment Management: Learning from the Australian Experience for the Murray-Darling Basin. CSIRO Sustainable Ecosystems, Canberra.

Benson, D., Lorenzoni, I., Cook, H., 2016. Evaluating social learning in England flood risk management: An ‘individual-community interaction’ perspective. Environ. Sci. Policy, Participatory and Collaborative Governance for Sustainable Flood Risk Management: An emerging research agenda 55, 326–334. https://doi.org/10.1016/j.envsci.2015.05.013

Berkes, F., 1994. Co-management: Bridging the two solitudes 22, 18–20.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T.M., Evans, L.S., Kotschy, K., Leitch, A.M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M.D., Schoon, M.L., Schultz, L., West, P.C., 2012. Toward Principles for Enhancing the Resilience of Ecosystem Services. Annu. Rev. Environ. Resour. 37, 421–448. https://doi.org/10.1146/annurev-environ-051211-123836

Blowers, A., 2017. The Limits of Power: The Politics of Local Planning Policy. Elsevier.

Bonfield, P., 2016. The Property Flood Resilience Action Plan. Department for Environment, Food & Rural Affairs.

Bracken, L.J., Bulkeley, H.A., Whitman, G., 2015. Transdisciplinary research: understanding the stakeholder perspective. J. Environ. Plan. Manag. 58, 1291–1308. https://doi.org/10.1080/09640568.2014.921596

Bracken, L.J., Oughton, E.A., Donaldson, A., Cook, B.R., Forrester, J., Spray, C., Cinderby, S., Passmore, D., Bissett, N., 2016. Flood risk management, an approach to managing cross-border hazards. Nat. Hazards. https://doi.org/10.1007/s11069-016-2284-2

Bradbrook, K.F., Lane, S.N., Waller, S.G., Bates, P.D., 2004. Two dimensional diffusion wave modelling of flood inundation using a simplified channel representation. Int. J. River Basin Manag. 2, 211–223. https://doi.org/10.1080/15715124.2004.9635233

Brandeis, M.-N.W., Carrera Zamanillo, M.I., 2017. Finding meaningful participation in volunteer geographic information and citizen science: a case comparison in environmental application. Cartogr. Geogr. Inf. Sci. 44, 539–550. https://doi.org/10.1080/15230406.2016.1221779

Breitbart, M.M., 2010. Participatory Research Methods, in: Clifford, N., Cope, M., Gillespie, T., French, S. (Eds.), Key Methods in Geography. SAGE, London, pp. 141–156.

Brody, S.D., Kang, J.E., Bernhardt, S., 2010. Identifying factors influencing flood mitigation at the local level in Texas and Florida: the role of organizational capacity. Nat. Hazards 52, 167–184. https://doi.org/10.1007/s11069-009-9364-5

Bubeck, P., Botzen, W.J.W., Aerts, J.C.J.H., 2012. A Review of Risk Perceptions and Other Factors that Influence Flood Mitigation Behavior: Review of Flood Risk Perceptions. Risk Anal. 32, 1481–1495. https://doi.org/10.1111/j.1539-6924.2011.01783.x

Bucchi, M., Neresini, F., 2008. Science and Public Participation, in: Hackett, E.J., Amsterdamska, O., Lynch, M., Wajcman, J. (Eds.), The Handbook of Science and Technology Studies. MIT Press ; Published in cooperation with the Society for the Social Studies of Science, Cambridge, Mass, pp. 449–472.

Bulkely, H., Mol, A.P.J., 2003. Participation and Environmental Governance: Consensus, Ambivalence and Debate. Environ. Values 12, 143–154.

Bulley, D., 2013. Producing and Governing Community (through) Resilience. Politics 33, 265–275. https://doi.org/10.1111/1467-9256.12025

Burningham, K., Fielding, J., Thrush, D., 2008. 'It'll never happen to me': understanding public awareness of local flood risk. Disasters 32, 216–238. https://doi.org/10.1111/j.1467-7717.2007.01036.x

Burns, W.J., Slovic, P., 2012. Risk Perception and Behaviors: Anticipating and Responding to Crises. Risk Anal. 32, 579–582. https://doi.org/10.1111/j.1539-6924.2012.01791.x

Butler, C., Pidgeon, N., 2011. From 'Flood Defence' to 'Flood Risk Management': Exploring Governance, Responsibility, and Blame. Environ. Plan. C Gov. Policy 29, 533–547. https://doi.org/10.1068/c09181j

Butterworth, J., Warner, J.F., Moriarty, P., Smits, S., Batchelor, C., 2010. Finding practical approaches to integrated water resources management. Water Altern. 3, 68–81.

Cabinet Office, 2011. Strategic National Framework on Community Resilience. Cabinet Office, London.

Callon, M., 1999. The Role of Lay People in the Production and Dissemination of Scientific Knowledge. Sci. Technol. Soc. 4, 81–94. https://doi.org/10.1177/097172189900400106

Carpenter, S., Walker, B., Anderies, J.M., Abel, N., 2001. From Metaphor to Measurement: Resilience of What to What? Ecosystems 4, 765–781. https://doi.org/10.1007/s10021-001-0045-9

Cash, D.W., Adger, W.N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., Young, O., 2006. Scale and Cross-Scale Dynamics: Governance and Information in a Multilevel World. Ecol. Soc. 11.

Challies, E., Newig, J., Thaler, T., Kochskämper, E., Levin-Keitel, M., 2016. Participatory and collaborative governance for sustainable flood risk management: An emerging research agenda. Environ. Sci. Policy, Participatory and Collaborative Governance for Sustainable Flood Risk Management: An emerging research agenda 55, 275–280. https://doi.org/10.1016/j.envsci.2015.09.012

Chandler, D., 2017. Securing the Anthropocene? International policy experiments in digital hacktivism: A case study of Jakarta. Secur. Dialogue 48, 113–130. https://doi.org/10.1177/0967010616677714

Chandler, D., 2014. Beyond neoliberalism: resilience, the new art of governing complexity. Resilience 2, 47–63. https://doi.org/10.1080/21693293.2013.878544

Chandler, D., 2013. Resilience and the Autotelic Subject: Toward a Critique of the Societalization of Security. Int. Polit. Sociol. 7, 210–226. https://doi.org/10.1111/ips.12018

Charmaz, K., 2011. A Constructivist Grounded Theory Analysis of Losing and Regaining a Valued Self, in: Wertz, F.J. (Ed.), Five Ways of Doing Qualitative Analysis : Phenomenological Psychology, Grounded Theory, Discourse

Analysis, Narrative Research, and Intuitive Inquiry. Guilford Press, New York, pp. 165–204.

Chatterton, J., Viavattene, C., Morris, J., Penning-Rowsell, E., Tapsell, S., 2010. The costs of the summer 2007 floods in England (No. SC070039), Flood and Coastal Erosion Risk Management Research and Development Programme. Environment Agency, Bristol.

Chow, V.T., 1959. Open-channel hydraulics, McGraw-Hill civil engineering series. McGraw-Hill, New York.

Clark, A., Emmel, N., 2008. Walking interviews: more than walking and talking. Presented at the 'Peripatetic Practices': a workshop on walking, London.

Coates, T., 2015. Understanding local community construction through flooding: the 'conscious community' and the possibilities for locally based communal action: Understanding local community construction through flooding. Geo Geogr. Environ. n/a-n/a. https://doi.org/10.1002/geo2.6

Coates, T., 2010. Conscious community: belonging, identities and networks in local communities' response to flooding (PhD). Middlesex University, Middlesex.

Cobby, D.M., Mason, D.C., Horritt, M.S., Bates, P.D., 2003. Two-dimensional hydraulic flood modelling using a finite-element mesh decomposed according to vegetation and topographic features derived from airborne scanning laser altimetry. Hydrol. Process. 17, 1979–2000. https://doi.org/10.1002/hyp.1201

Coles, D., Yu, D., Wilby, R.L., Green, D., Herring, Z., 2017. Beyond 'flood hotspots': Modelling emergency service accessibility during flooding in York, UK. J. Hydrol. 546, 419–436. https://doi.org/10.1016/j.jhydrol.2016.12.013

Collenteur, R.A., Moel, H. de, Jongman, B., Baldassarre, G.D., 2015. The failed-levee effect: Do societies learn from flood disasters? Nat. Hazards 76, 373–388. https://doi.org/10.1007/s11069-014-1496-6

Collins, K., Blackmore, C., Morris, D., Watson, D., 2007. A systemic approach to managing multiple perspectives and stakeholding in water catchments: some findings from three UK case studies. Environ. Sci. Policy, Social Learning: an alternative policy instrument for managing in the context of Europe's water 10, 564–574. https://doi.org/10.1016/j.envsci.2006.12.005

Collins, K., Ison, R., 2009. Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. Environ. Policy Gov. 19, 358–373. https://doi.org/10.1002/eet.523

Committee on Climate Change, 2016. UK Climate Change Risk Assessment 2017 Synthesis report: priorities for the next five years. Committee on Climate Change, London.

Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., Böhner, J., 2015. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geosci Model Dev 8, 1991–2007. https://doi.org/10.5194/gmd-8-1991-2015

Cook, B.R., Atkinson, M., Chalmers, H., Comins, L., Cooksley, S., Deans, N., Fazey, I., Fenemor, A., Kesby, M., Litke, S., Marshall, D., Spray, C., 2013a. Interrogating participatory catchment organisations: cases from Canada, New Zealand, Scotland and the Scottish–English Borderlands. Geogr. J. 179, 234–247. https://doi.org/10.1111/j.1475-4959.2012.00492.x

Cook, B.R., Kesby, M., Fazey, I., Spray, C., 2013b. The persistence of “normal” catchment management despite the participatory turn: Exploring the power effects of competing frames of reference. Soc. Stud. Sci. 43, 754–779. https://doi.org/10.1177/0306312713478670

Cook, H., Benson, D., Inman, A., Jordan, A., Smith, L., 2012. Catchment management groups in England and Wales: extent, roles and influences. Water Environ. J. 26, 47–55. https://doi.org/10.1111/j.1747-6593.2011.00262.x

Cooke, B., Kothari, U. (Eds.), 2001. Participation: the new tyranny? Zed Books, London ; New York.

Cope, M., Elwood, S., 2009. Introduction: Qualitative GIS: Forging Mixed Methods through Representations, Analytical Innovations, and Conceptual Engagements, in: Cope, M., Elwood, S. (Eds.), Qualitative GIS: A Mixed Methods Approach. Sage, Thousand Oaks, CA, pp. 1–12.

Crower, R.A., 2009. Fluvial Design Guide. Environment Agency, Bristol.

Cutter, S.L., 2016. Resilience to What? Resilience for Whom? Geogr. J. 182, 110–113. https://doi.org/10.1111/geoj.12174

Davies, R., 2015. Two-Thirds of UK Households Fail To Check Flood Risk Levels. FloodList.

Davoudi, S., 2016. Resilience and the governmentality of unknowns, in: Bevir, M. (Ed.), Governmentality after Neoliberalism, Routledge Studies in Governance and Public Policy. Routledge, New York, pp. 152–170.

Davoudi, S., 2014. Climate Change, Securitisation of Nature, and Resilient Urbanism. Environ. Plan. C Gov. Policy 32, 360–375. https://doi.org/10.1068/c12269

Davoudi, S., 2012. Resilience: A Bridging Concept or a Dead End?, in: Porter, L., Davoudi, S. (Eds.), Planning Theory & Practice. pp. 299–307.

Davoudi, S., Brooks, E., Mehmood, A., 2013. Evolutionary Resilience and Strategies for Climate Adaptation. Plan. Pract. Res. 28, 307–322. https://doi.org/10.1080/02697459.2013.787695

de Moel, H., van Alphen, J., Aerts, J.C.J.H., 2009. Flood maps in Europe – methods, availability and use. Nat Hazards Earth Syst Sci 9, 289–301. https://doi.org/10.5194/nhess-9-289-2009

Deeming, H., Whittle, R., Medd, W., 2012. Investigating Resilience, Through “Before and After” Perspectives on Residual Risk, in: Bennett, S. (Ed.), Innovative Thinking in Risk, Crisis, and Disaster Management. Gower, Farnham, Surrey, England ; Burlington, VT.

Defra, 2016. Catchment Partnerships Action Fund: Environment Agency report 2015-16. Defra, London.

Defra, 2013. Catchment Based Approach: Improving the quality of our water environment - A policy framework to encourage the wider adoption of an integrated Catchment Based Approach to improving the quality of our water environment (No. PB 13934). Defra, London.

Defra, 2005. Making space for water - Taking forward a new Government strategy for flood and coastal erosion risk management in England. Defra Publications.

Degrossi, L., De Albuquerque, J., Fava, M., Mendiondo, E., 2014. Flood Citizen Observatory: a crowdsourcing-based approach for flood risk management in Brazil.

Dekens, J., 2007. Local Knowledge for Disaster Preparedness: A Literature Review. International Centre for Integrated Mountain Development, Kathmandu.

Demeritt, D., Norbert, S., 2014. Models of best practice in flood risk communication and management. Environ. Hazards 13, 313–328. https://doi.org/10.1080/17477891.20l4.924897

Department for International Development, 2011. Defining disaster resilience: a DFID approach paper. London.

DeVerteuil, G., Golubchikov, O., 2016. Can resilience be redeemed? City 20, 143–151. https://doi.org/10.1080/13604813.2015.1125714

Donaldson, A., Ward, N., Bradley, S., 2010. Mess among disciplines: interdisciplinarity in environmental research. Environ. Plan. A 42, 1521–1536.

Dowling, R., Lloyd, K., Suchet-Pearson, S., 2016. Qualitative methods 1: Enriching the interview. Prog. Hum. Geogr. 40, 679–686. https://doi.org/10.1177/0309132515596880

Dungumaro, E.W., Madulu, N.F., 2003. Public participation in integrated water resources management: the case of Tanzania. Phys. Chem. Earth Parts ABC 28, 1009–1014. https://doi.org/10.1016/j.pce.2003.08.042

Dunn, C.E., 2007. Participatory GIS a people's GIS? Prog. Hum. Geogr. 31, 616–637. https://doi.org/10.1177/0309132507081493

Eden, S., 1996. Public participation in environmental policy: considering scientific, counter-scientific and non-scientific contributions. Public Underst. Sci. 5, 183–204. https://doi.org/10.1088/0963-6625/5/3/001

Edwards, C., 2009. Resilient Nation. Demos, London.

Environment Agency, 2018. Catchment Data Explorer - Twizell Burn from Source to Cong Burn [WWW Document]. EA Catchment Plan. Linked Data Portal. URL http://environment.data.gov.uk/catchment-planning/WaterBody/GB103024077590 (accessed 3.26.18).

Environment Agency, 2016. Impact Report Winter Flooding 2015-16 - Northumberland, Durham and Tees Area.

Environment Agency, 2015. Catchment Partnerships in Operation.

Environment Agency, 2012. Recommendations for flood mapping in England and Wales: Findings from the RISK MAP ERA-NET CRUE (No. SC090015), Flood and Coastal Erosion Risk Management R&D Programme. Environment Agency, Bristol.

Environment Agency, 2011. National flood and coastal erosion risk management strategy for England [WWW Document]. URL https://www.gov.uk/government/publications/national-flood-and-coastal-erosion-risk-management-strategy-for-england (accessed 10.13.14).

Environment Agency, 2010. Flood and Coastal Risk Management Risk Mapping Strategy 2010–2015.

Environment Agency, 2009. Flooding in England: A National Assessment of Flood Risk.

Environment, Food and Rural Affairs Committee, 2016. Future Flood Prevention - Second Report of Session 2016–17. House of Commons, London.

Environment, Food and Rural Affairs Select Committee, 2016. Future flood prevention [WWW Document]. www.parliament.uk. URL http://www.publications.parliament.uk/pa/cm201617/cmselect/cmenvfru/115/11502.htm (accessed 11.15.16).

European Commission, Directorate-General for the Environment, 2003. Public participation in relation to the water framework directive No 8. OPOCE, Luxembourg.

European Environment Agency, 2008. Floods. Eur. Environ. Agency.

European Parliament and the Council, 2007. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks.

Evans, J., Jones, P., 2011. The walking interview: Methodology, mobility and place. Appl. Geogr. 31, 849–858. https://doi.org/10.1016/j.apgeog.2010.09.005

Evers, M., Jonoski, A., Almoradie, A., Lange, L., 2016. Collaborative decision making in sustainable flood risk management: A socio-technical approach and tools for participatory governance. Environ. Sci. Policy, Participatory and Collaborative Governance for Sustainable Flood Risk Management: An emerging research agenda 55, 335–344. https://doi.org/10.1016/j.envsci.2015.09.009

EXCIMAP, 2007a. Handbook on good practices for flood mapping in Europe.

EXCIMAP, 2007b. Atlas of Flood Maps. Netherlands Ministry of Transport, Public Works and Water Management, The Hague.

Falkenmark, M., Gottschalk, L., Lundqvist, J., Wouters, P., 2004. Towards integrated catchment management: increasing the dialogue between scientists, policy-makers and stakeholders. Int. J. Water Resour. Dev. 20, 297–309. https://doi.org/10.1080/0790062042000248619

Fenemor, A., Phillips, C., Allen, W., Young, R., Harmsworth, G., Bowden, B., Basher, L., Gillespie, P., Kilvington, M., Davies-Colley, R., Dymond, J., Cole, A., Lauder, G., Davie, T., Smith, R., Markham, S., Deans, N., Stuart, B., Atkinson, M., Collins, A., 2011. Integrated catchment management — interweaving social process and science knowledge. N. Z. J. Mar. Freshw. Res. 45, 313–331. https://doi.org/10.1080/00288330.2011.593529

Fernández, A., Najafi, M.R., Durand, M., Mark, B.G., Moritz, M., Jung, H.C., Neal, J., Shastry, A., Laborde, S., Phang, S.C., Hamilton, I.M., Xiao, N., 2016. Testing the skill of numerical hydraulic modeling to simulate spatiotemporal flooding patterns in the Logone floodplain, Cameroon. J. Hydrol. 539, 265–280. https://doi.org/10.1016/j.jhydrol.2016.05.026

Feyen, L., Dankers, R., Bódis, K., Salamon, P., Barredo, J.I., 2012. Fluvial flood risk in Europe in present and future climates. Clim. Change 112, 47–62. https://doi.org/10.1007/s10584-011-0339-7

Fielding, J., Burningham, K., Thrush, D., Catt, R., 2007. Public response to flood warning (R&D Technical Report No. SC020116), Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme. Environment Agency, Bristol.

Fischer, F., 2000. Citizens, experts, and the environment: the politics of local knowledge. Duke University Press, Durham, NC.

Fischhoff, B., Bostrom, A., Quadrel, M.J., 1993. Risk Perception and Communication. Annu. Rev. Public Health 14, 183–203. https://doi.org/10.1146/annurev.pu.14.050193.001151

Fish, R.D., Ioris, A.A.R., Watson, N.M., 2010. Integrating water and agricultural management: Collaborative governance for a complex policy problem. Sci. Total Environ., Special Section: Integrating Water and Agricultural Management Under Climate Change 408, 5623–5630. https://doi.org/10.1016/j.scitotenv.2009.10.010

Fisher, H., 2015. Public dialogues on flood risk communication (No. SC120010/R1), Flood and Coastal Erosion Risk Management Research and Development Programme. Environment Agency, Bristol.

Fishpal.com, n.d. FishPal.com [WWW Document]. URL http://www.fishpal.com/ (accessed 4.12.17).

Flood Information Service, n.d. Flood information service [WWW Document]. URL https://flood-warning-information.service.gov.uk/ (accessed 4.12.17).

Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. Glob. Environ. Change 16, 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T., Rockström, J., 2010. Resilience Thinking: Integrating Resilience, Adaptability and Transformability. Ecol. Soc. 15. https://doi.org/10.5751/ES-03610-150420

Fritsch, O., 2017. Integrated and adaptive water resources management: exploring public participation in the UK. Reg. Environ. Change 17, 1933–1944. https://doi.org/10.1007/s10113-016-0973-8

Frodeman, R., Pacheco, R.C.D.S., 2016. The Oxford Handbook of Interdisciplinarity. Oxford University Press.

García-Pintado, J., Neal, J.C., Mason, D.C., Dance, S.L., Bates, P.D., 2013. Scheduling satellite-based SAR acquisition for sequential assimilation of water level observations into flood modelling. J. Hydrol. 495, 252–266. https://doi.org/10.1016/j.jhydrol.2013.03.050

Gaynor, N., 2014. The tyranny of participation revisited: international support to local governance in Burundi. Community Dev. J. 49, 295–310. https://doi.org/10.1093/cdj/bst031

Gilissen, H.K., Alexander, M., Matczak, P., Pettersson, M., Bruzzone, S., 2016. A framework for evaluating the effectiveness of flood emergency management systems in Europe. Ecol. Soc. 21. https://doi.org/10.5751/ES-08723-210427

Gobeyn, S., Van Wesemael, A., Neal, J., Lievens, H., Adams, K., De Vleeschouwer, N., Vernieuwe, H., Schumann, G.J.P., Di Baldassarre, G., Baets, B., Bates, P.D., Verhoest, N.E.C., 2017. Impact of the timing of a SAR image acquisition on the calibration of a flood inundation model. Adv. Water Resour. 100, 126–138. https://doi.org/10.1016/j.advwatres.2016.12.005

Gobo, G., 2011. Ethnography, in: Silverman, D. (Ed.), Qualitative Research. SAGE, London.

Goodchild, M.F., 2007. Citizens as sensors: the world of volunteered geography. GeoJournal 69, 211–221. https://doi.org/10.1007/s10708-007-9111-y

Goodchild, M.F., Glennon, J.A., 2010. Crowdsourcing geographic information for disaster response: a research frontier. Int. J. Digit. Earth 3, 231–241. https://doi.org/10.1080/17538941003759255

Goodwin, M., 2009. Governance, in: Kitchin, R., Thrift, N. (Eds.), International Encyclopedia of Human Geography. Elsevier, Oxford, pp. 593–599. https://doi.org/10.1016/B978-008044910-4.00782-3

Granell, C., Ostermann, F.O., 2016. Beyond data collection: Objectives and methods of research using VGI and geo-social media for disaster management. Comput. Environ. Urban Syst. 59, 231–243. https://doi.org/10.1016/j.compenvurbsys.2016.01.006

Great Britain, 2010. Flood and Water Management Act.

Greening the Twizell Partnership, Personal Communication. Greening the Twizell Partnership Agreement.

Grothmann, T., Reusswig, F., 2006. People at Risk of Flooding: Why Some Residents Take Precautionary Action While Others Do Not. Nat. Hazards 38, 101–120. https://doi.org/10.1007/s11069-005-8604-6

Groundworks NE & Cumbria, 2015. Twizell Burn Green Infrastructure Action Plan. Groundworks NE & Cumbria, Annfield Plain.

Grove, K., Chandler, D., 2017. Introduction: resilience and the Anthropocene: the stakes of 'renaturalising' politics. Resilience 5, 79–91. https://doi.org/10.1080/21693293.2016.1241476

Hagemeier-Klose, M., Wagner, K., 2009. Evaluation of flood hazard maps in print and web mapping services as information tools in flood risk communication. Nat Hazards Earth Syst Sci 9, 563–574. https://doi.org/10.5194/nhess-9-563-2009

Haklay, M., Antoniou, V., Basiouka, S., Soden, R., Mooney, P., 2014. Crowdsourced geographic information use in government (Report to GFDRR). World Bank, London.

Hardy, R.J., Bates, P.D., Anderson, M.G., 1999. The importance of spatial resolution in hydraulic models for floodplain environments. J. Hydrol. 216, 124–136. https://doi.org/10.1016/S0022-1694(99)00002-5

Harries, T., 2008. Feeling secure or being secure? Why it can seem better not to protect yourself against a natural hazard. Health Risk Soc. 10, 479–490. https://doi.org/10.1080/13698570802381162

Harris, R., 2013. The Catchment Based Approach. Presented at the IAH conference on Groundwater and Catchment Management, Unpublished, Tullamore. https://doi.org/10.13140/2.1.5152.2246

Haworth, B., Bruce, E., 2015. A Review of Volunteered Geographic Information for Disaster Management: A Review of VGI for Disaster Management. Geogr. Compass 9, 237–250. https://doi.org/10.1111/gec3.12213

Hayward, C., Simpson, L., Wood, L., 2004. Still Left out in the Cold: Problematising Participatory Research and Development. Sociol. Rural. 44, 95–108. https://doi.org/10.1111/j.1467-9523.2004.00264.x

Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliott, M., Feld, C.K., Heiskanen, A.-S., Johnson, R.K., Moe, J., Pont, D., Solheim, A.L., de Bund, W. van, 2010. The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future. Sci. Total Environ. 408, 4007–4019. https://doi.org/10.1016/j.scitotenv.2010.05.031

Hickey, S., Mohan, G. (Eds.), 2004. Participation, from tyranny to transformation?: exploring new approaches to participation in development. ZED Books ; Distributed exclusively in the U.S. by Palgrave Macmillan, London ; New York : New York.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nat. Clim. Change 3, nclimate1911. https://doi.org/10.1038/nclimate1911

HM Government, 2016. National Flood Resilience Review. HM Government, London.

Hogan Carr, R., Montz, B., Maxfield, K., Hoekstra, S., Semmens, K., Goldman, E., 2016. Effectively Communicating Risk and Uncertainty to the Public: Assessing the

National Weather Service’s Flood Forecast and Warning Tools. Bull. Am. Meteorol. Soc. 97, 1649–1665. https://doi.org/10.1175/BAMS-D-14-00248.1

Holling, C.S., 1973. Resilience and Stability of Ecological Systems. Annu. Rev. Ecol. Syst. 4, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Hopkins, J., Warburton, J., 2015. Local perception of infrequent, extreme upland flash flooding: prisoners of experience? Disasters 39, 546–569. https://doi.org/10.1111/disa.12120

Horita, F.E.A., Albuquerque, J.P. de, Degrossi, L.C., Mendiondo, E.M., Ueyama, J., 2015. Development of a spatial decision support system for flood risk management in Brazil that combines volunteered geographic information with wireless sensor networks. Comput. Geosci. 80, 84–94. https://doi.org/10.1016/j.cageo.2015.04.001

Horritt, M.., Bates, P.D., 2001. Effects of spatial resolution on a raster based model of flood flow. J. Hydrol. 253, 239–249. https://doi.org/10.1016/S0022-1694(01)00490-5

Hung, K.-C., Kalantari, M., Rajabifard, A., 2016. Methods for assessing the credibility of volunteered geographic information in flood response: A case study in Brisbane, Australia. Appl. Geogr. 68, 37–47. https://doi.org/10.1016/j.apgeog.2016.01.005

Hunter, N.M., Bates, P.D., Horritt, M.S., Wilson, M.D., 2007. Simple spatially-distributed models for predicting flood inundation: A review. Geomorphology 90, 208–225. https://doi.org/10.1016/j.geomorph.2006.10.021

Hunter, N.M., Horritt, M.S., Bates, P.D., Wilson, M.D., Werner, M.G.F., 2005. An adaptive time step solution for raster-based storage cell modelling of floodplain inundation. Adv. Water Resour. 28, 975–991. https://doi.org/10.1016/j.advwatres.2005.03.007

Jarvis, A.P., Younger, P.L., 1999. Design, Construction and Performance of a Full-Scale Compost Wetland for Mine-Spoil Drainage Treatment at Quaking Houses. Water Environ. J. 13, 313–318. https://doi.org/10.1111/j.1747-6593.1999.tb01054.x

Jemberu, W., Baartman, J.E.M., Fleskens, L., Ritsema, C.J., 2018. Participatory assessment of soil erosion severity and performance of mitigation measures using stakeholder workshops in Koga catchment, Ethiopia. J. Environ. Manage. 207, 230–242. https://doi.org/10.1016/j.jenvman.2017.11.044

Johnson, C.L., Priest, S.J., 2008. Flood Risk Management in England: A Changing Landscape of Risk Responsibility? Int. J. Water Resour. Dev. 24, 513–525. https://doi.org/10.1080/07900620801923146

Jones, P., Bunce, G., Evans, J., Gibbs, H., Hein, J.R., 2008. Exploring Space and Place With Walking Interviews. J. Res. Pract. 4, 2.

Jones, P., Evans, J., 2012. The spatial transcript: analysing mobilities through qualitative GIS. Area 44, 92–99. https://doi.org/10.1111/j.1475-4762.2011.01058.x

Jordan, A., Wurzel, R.K.W., Zito, A., 2005. The Rise of ‘New’ Policy Instruments in Comparative Perspective: Has Governance Eclipsed Government? Polit. Stud. 53, 477–496. https://doi.org/10.1111/j.1467-9248.2005.00540.x

Jung, Y., Kim, Dongkyun, Kim, Dongwook, Kim, M., Lee, S.O., 2014. Simplified Flood Inundation Mapping Based On Flood Elevation-Discharge Rating Curves Using Satellite Images in Gauged Watersheds. Water 6, 1280–1299. https://doi.org/10.3390/w6051280

Kareiva, P., Fuller, E., 2016. Beyond Resilience: How to Better Prepare for the Profound Disruption of the Anthropocene. Glob. Policy 7, 107–118. https://doi.org/10.1111/1758-5899.12330

Kasperson, R.E., Stallen, P.J., 2012. Communicating Risks to the Public: International Perspectives. Springer Science & Business Media.

Kemp, P., Griffiths, J., 1999. Quaking Houses: art, science and the community ; a collaborative approach to water pollution. Jon Carpenter ; distributor, Paul and Company, Charlbury, Oxfordshire, England : Concord, MA.

Kesby, M., 2000. Participatory diagramming: deploying qualitative methods through an action research epistemology. Area 32, 423–435.

Kilvington, M., Allen, W., Fenemor, A., 2011. Three frameworks to understand and manage social processes for integrated catchment management. N. Z. J. Mar. Freshw. Res. 45, 541–555. https://doi.org/10.1080/00288330.2011.593182

Kindon, S.L., Pain, R., Kesby, M. (Eds.), 2007a. Participatory action research approaches and methods: connecting people, participation and place, Routledge studies in human geography. Routledge, London ; New York.

Kindon, S.L., Pain, R., Kesby, M., 2007b. Participatory Action Research - Origins, approaches and methods, in: Kindon, S.L., Pain, R., Kesby, M. (Eds.), Participatory Action Research Approaches and Methods: Connecting People, Participation and Place, Routledge Studies in Human Geography. Routledge, London ; New York, pp. 9–18.

Kirk, E.A., Reeves, A.D., Blackstock, K.L., 2007. Path Dependency and the Implementation of Environmental Regulation. Environ. Plan. C Gov. Policy 25, 250–268. https://doi.org/10.1068/c0512j

Klijn, F., Samuels, P., Os, A.V., 2008. Towards flood risk management in the EU: State of affairs with examples from various European countries. Int. J. River Basin Manag. 6, 307–321. https://doi.org/10.1080/15715124.2008.9635358

Klonner, C., Marx, S., Usán, T., Porto de Albuquerque, J., Höfle, B., 2016. Volunteered Geographic Information in Natural Hazard Analysis: A Systematic Literature Review of Current Approaches with a Focus on Preparedness and Mitigation. ISPRS Int. J. Geo-Inf. 5, 103. https://doi.org/10.3390/ijgi5070103

Knigge, L., Cope, M., 2006. Grounded visualization: integrating the analysis of qualitative and quantitative data through grounded theory and visualization. Environ. Plan. A 38, 2021 – 2037. https://doi.org/10.1068/a37327

Kundzewicz, Z.W., Pińskwar, I., Brakenridge, G.R., 2017. Changes in river flood hazard in Europe: a review. Hydrol. Res. nh2017016. https://doi.org/10.2166/nh.2017.016

Kusenbach, M., 2003. Street Phenomenology: The Go-Along as Ethnographic Research Tool. Ethnography 4, 455–485. https://doi.org/10.1177/146613810343007

Lamond, J.E., 2014. The role of flood memory in the impact of repeat flooding on mental health, in: Proverbs, D.G., Brebbia, C.A. (Eds.), Flood Recovery, Innovation and Response IV, WIT Transactions on Ecology and the Environment. WITPress, Southampton.

Lamond, J.E., Joseph, R.D., Proverbs, D.G., 2015. An exploration of factors affecting the long term psychological impact and deterioration of mental health in flooded households. Environ. Res. 140, 325–334. https://doi.org/10.1016/j.envres.2015.04.008

Landmark Chambers, 2014. Consultation: The Legal Reqiurements.

Landström, C., Whatmore, S.J., Lane, S.N., Odoni, N.A., Ward, N., Bradley, S., 2011. Coproducing flood risk knowledge: redistributing expertise in critical 'participatory modelling.' Environ. Plan. A 43, 1617–1633. https://doi.org/10.1068/a43482

Lane, S.N., 2012. Ethical Risk Management, but Without Risk Communication?, in: Kearnes, M., Klauser, F.R., Lane, S.N. (Eds.), Critical Risk Research Practices, Politics, and Ethics. Wiley, Hoboken, N.J.

Lane, S.N., Landström, C., Whatmore, S.J., 2011a. Imagining flood futures: risk assessment and management in practice. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 369, 1784–1806. https://doi.org/10.1098/rsta.2010.0346

Lane, S.N., November, V., Landström, C., Whatmore, S.J., 2013. Explaining Rapid Transitions in the Practice of Flood Risk Management. Ann. Assoc. Am. Geogr. 103, 330–342. https://doi.org/10.1080/00045608.2013.754689

Lane, S.N., Odoni, N., Landström, C., Whatmore, S.J., Ward, N., Bradley, S., 2011b. Doing flood risk science differently: an experiment in radical scientific method. Trans. Inst. Br. Geogr. 36, 15–36. https://doi.org/10.1111/j.1475-5661.2010.00410.x

Lanfranchi, V., Wrigley, S.N., Ireson, N., Ciravegna, F., Wehn, U., 2014. Citizens' Observatories for Situation Awareness in Flooding, in: Proceedings of the 11th International ISCRAM Conference. Pennsylvania.

Lee, M., Abbot, C., 2003. The Usual Suspects? Public Participation Under the Aarhus Convention. Mod. Law Rev. 66, 80–108. https://doi.org/10.1111/1468-2230.6601004

Leedal, D., Weerts, A.H., Smith, P.J., Beven, K.J., 2013. Application of data-based mechanistic modelling for flood forecasting at multiple locations in the Eden catchment in the National Flood Forecasting System (England and Wales). Hydrol Earth Syst Sci 17, 177–185. https://doi.org/10.5194/hess-17-177-2013

Leedal, D., Weerts, A.H., Smith, P.J., Beven, K.J., 2012. A data based mechanistic real-time flood forecasting module for NFFS FEWS. Hydrol. Earth Syst. Sci. Discuss. 9, 7271–7296. https://doi.org/10.5194/hessd-9-7271-2012

Lerner, D.N., Zheng, C., 2011. Integrated catchment management: path to enlightenment. Hydrol. Process. 25, 2635–2640. https://doi.org/10.1002/hyp.8064

Lisa, E., Schipper, F., Langston, L., 2015. A comparative overview of resilience measurement frameworks. Overseas Development Institute, London.

Ludwig, D., 2001. The Era of Management Is Over. Ecosystems 4, 758–764. https://doi.org/10.1007/s10021-001-0044-x

Lundgren, R.E., McMakin, A.H., 2018. Risk Communication: A Handbook for Communicating Environmental, Safety, and Health Risks. John Wiley & Sons.

Maclean, K., Cuthill, M., Ross, H., 2014. Six attributes of social resilience. J. Environ. Plan. Manag. 57, 144–156. https://doi.org/10.1080/09640568.2013.763774

Manyena, S.B., 2006. The Concept of Resilience Revisited. Disasters 30, 434–450. https://doi.org/10.1111/j.0361-3666.2006.00331.x

Margerum, R.D., 1999. Integrated Environmental Management: The Foundations for Successful Practice. Environ. Manage. 24, 151–166. https://doi.org/10.1007/s002679900223

Marques, B., McIntosh, J., Campays, P., 2018. Participatory Design for Under-Represented Communities: A Collaborative Design-Led Research Approach for Place-Making. Handb. Res. Civ. Engagem. Soc. Change Contemp. Soc. 1–15. https://doi.org/10.4018/978-1-5225-4197-4.ch001

Marsh, T., Kirby, C., Muchan, K., Barker, L., Henderson, E., Hannaford, J., 2016. The winter floods of 2015/2016 in the UK - a review. Centre for Ecology and Hydrology, Wallingford.

Marshall, K., Blackstock, K.L., Dunglinson, J., 2010. A contextual framework for understanding good practice in integrated catchment management. J. Environ. Plan. Manag. 53, 63–89. https://doi.org/10.1080/09640560903399780

Mattijssen, T.J.M., van der Jagt, A.P.N., Buijs, A.E., Elands, B.H.M., Erlwein, S., Lafortezza, R., 2017. The long-term prospects of citizens managing urban green space: From place making to place-keeping? Urban For. Urban Green., Special feature:TURFGRASS 26, 78–84. https://doi.org/10.1016/j.ufug.2017.05.015

Maynard, C.M., 2013. How public participation in river management improvements is affected by scale: Public participation in river management improvements. Area 45, 230–238. https://doi.org/10.1111/area.12015

Mays, N., Pope, C., 2000. Assessing quality in qualitative research. BMJ 320, 50–52. https://doi.org/10.1136/bmj.320.7226.50

McBain, W., Wilkes, D., Retter, M., Construction Industry Research and Information Association., 2010. Flood resilience and resistance for critical infrastructure. CIRIA, London.

McCall, M.K., 2008. Participatory Mapping and Participatory GIS (PGIS) for CRA, Community DRR and Hazard Assessment.

McCallum, I., Liu, W., See, L., Mechler, R., Keating, A., Hochrainer-Stigler, S., Mochizuki, J., Fritz, S., Dugar, S., Arestegui, M., Szoenyi, M., Bayas, J.-C.L., Burek, P., French, A., Moorthy, I., 2016. Technologies to Support Community Flood Disaster Risk Reduction. Int. J. Disaster Risk Sci. 7, 198–204. https://doi.org/10.1007/s13753-016-0086-5

McDougall, K., 2012. An assessment of the contribution of volunteered geographic information during recent natural disasters, in: Rajabifard, A., Coleman, D. (Eds.), Spatially Enabling Government, Industry and Citizens: Research and Development Perspectives. GSDI Association Press, Needham, MA, United States, pp. 201–214.

McEwen, L., Garde-Hansen, J., Holmes, A., Jones, O., Krause, F., 2017. Sustainable flood memories, lay knowledges and the development of community resilience to future flood risk. Trans. Inst. Br. Geogr. 42, 14–28. https://doi.org/10.1111/tran.12149

McEwen, L., Jones, O., Robertson, I., 2014. 'A glorious time?' Some reflections on flooding in the Somerset Levels. Geogr. J. 180, 326–337. https://doi.org/10.1111/geoj.12125

Mcquail, D., Windahl, S., 2015. Communication Models for the Study of Mass Communications. Routledge.

Mees, H., Crabbé, A., Alexander, M., Kaufmann, M., Bruzzone, S., Lévy, L., Lewandowski, J., 2016. Coproducing flood risk management through citizen involvement: insights from cross-country comparison in Europe. Ecol. Soc. 21. https://doi.org/10.5751/ES-08500-210307

Mees, H., Suykens, C., Crabbé, A., 2017. Evaluating Conditions for Integrated Water Resource Management at Sub-basin Scale. A Comparison of the Flemish Sub-basin Boards and Walloon River Contracts. Environ. Policy Gov. 27, 59–73. https://doi.org/10.1002/eet.1736

Meyer, V., Kuhlicke, C., Luther, J., Fuchs, S., Priest, S., Dorner, W., Serrhini, K., Pardoe, J., McCarthy, S., Seidel, J., Palka, G., Unnerstall, H., Viavattene, C., Scheuer, S., 2012. Recommendations for the user-specific enhancement of flood maps. Nat Hazards Earth Syst Sci 12, 1701–1716. https://doi.org/10.5194/nhess-12-1701-2012

Meyer, V., Kuhlicke, C., Luther, J., Unnerstall, H., Fuchs, S., Priest, S., Pardoe, J., McCarthy, S., Dorner, W., Seidel, J., Serrhini, K., Palka, G., Scheuer, S., 2011. CRUE Final Report RISK MAP – Improving Flood Risk Maps as a Means to Foster Public Participation and Raising Flood Risk Awareness: Toward Flood Resilient Communities (No. ERAC-CT-2004-515742), 2nd ERA-NET CRUE

Research Funding Initiative. General Directorate for Research in the European Commission.

Milojevic, A., Armstrong, B., Wilkinson, P., 2017. Mental health impacts of flooding: a controlled interrupted time series analysis of prescribing data in England. J. Epidemiol. Community Health 71, 970–973. https://doi.org/10.1136/jech-2017-208899

Ministry of Housing, Communities & Local Government, 2017. Consultation and pre-decision matters.

Mitchell, B., Hollick, M., 1993. Integrated catchment management in Western Australia: Transition from concept to implementation. Environ. Manage. 17, 735–743. https://doi.org/10.1007/BF02393894

Mokrech, M., Kebede, A.S., Nicholls, R.J., Wimmer, F., Feyen, L., 2015. An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe. Clim. Change 128, 245–260. https://doi.org/10.1007/s10584-014-1298-6

Moss, T., 2004. The governance of land use in river basins: prospects for overcoming problems of institutional interplay with the EU Water Framework Directive. Land Use Policy 21, 85–94. https://doi.org/10.1016/j.landusepol.2003.10.001

Mouratiadou, I., Moran, D., 2007. Mapping public participation in the Water Framework Directive: A case study of the Pinios River Basin, Greece. Ecol. Econ. 62, 66–76. https://doi.org/10.1016/j.ecolecon.2007.01.009

Muller, C. l., Chapman, L., Johnston, S., Kidd, C., Illingworth, S., Foody, G., Overeem, A., Leigh, R. r., 2015. Crowdsourcing for climate and atmospheric sciences: current status and future potential. Int. J. Climatol. 35, 3185–3203. https://doi.org/10.1002/joc.4210

Mulligan, M., Rogers, P., 2017. Looking at emergent and multi-scale governance through the lens of community formation. Resilience 0, 1–18. https://doi.org/10.1080/21693293.2017.1306157

Munich Re, 2013. Floods dominate natural catastrophe statistics in first half of 2013 [WWW Document]. URL https://www.munichre.com/en/media-relations/publications/press-releases/2013/2013-07-09-press-release/index.html (accessed 10.28.17).

Munro, A., Kovats, R.S., Rubin, G.J., Waite, T.D., Bone, A., Armstrong, B., English National Study of Flooding and Health Study Group, 2017. Effect of evacuation and displacement on the association between flooding and mental health outcomes: a cross-sectional analysis of UK survey data. Lancet Planet. Health 1, e134–e141. https://doi.org/10.1016/S2542-5196(17)30047-5

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I — A discussion of principles. J. Hydrol. 10, 282–290. https://doi.org/10.1016/0022-1694(70)90255-6

National Research Council, 2008. Public Participation in Environmental Assessment and Decision Making. National Academies Press.

Navarra, D.D., Cornford, T., 2005. ICT, Innovation and Public Management: Governance, Models and Alternatives for eGovernment Infastructures, in: ECIS 2005 Proceedings. Presented at the E uropean Conference on I nformation S ystems, p. 12.

Neal, J., Schumann, G., Bates, P.D., 2012. A subgrid channel model for simulating river hydraulics and floodplain inundation over large and data sparse areas. Water Resour. Res. 48. https://doi.org/10.1029/2012WR012514

Neal, J., Schumann, G., Fewtrell, T., Budimir, M., Bates, P.D., Mason, D., 2011. Evaluating a new LISFLOOD-FP formulation with data from the summer 2007 floods in Tewkesbury, UK: Evaluating a new LISFLOOD-FP formulation. J. Flood Risk Manag. 4, 88–95. https://doi.org/10.1111/j.1753-318X.2011.01093.x

Neal, J.C., Bates, P.D., Fewtrell, T.J., Hunter, N.M., Wilson, M.D., Horritt, M.S., 2009. Distributed whole city water level measurements from the Carlisle 2005 urban flood event and comparison with hydraulic model simulations. J. Hydrol. 368, 42–55. https://doi.org/10.1016/j.jhydrol.2009.01.026

Néelz, S., Pender, G., 2013. Benchmarking the latest generation of 2D hydraulic modelling packages (No. SC120002). Environment Agency, Bristol.

Nester, T., Komma, J., Blöschl, G., 2016. Real time flood forecasting in the Upper Danube basin. J. Hydrol. Hydromech. 64, 404–414. https://doi.org/10.1515/johh-2016-0033

Newig, J., Challies, E., Jager, N., Kochskämper, E., 2014. What Role for Public Participation in Implementing the EU Floods Directive? A Comparison With the Water Framework Directive, Early Evidence from Germany and a Research Agenda. Environ. Policy Gov. 24, 275–288. https://doi.org/10.1002/eet.1650

Newig, J., Koontz, T.M., 2014. Multi-level governance, policy implementation and participation: the EU's mandated participatory planning approach to implementing environmental policy. J. Eur. Public Policy 21, 248–267. https://doi.org/10.1080/13501763.2013.834070

Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., Crowston, K., 2012. The future of citizen science: emerging technologies and shifting paradigms. Front. Ecol. Environ. 10, 298–304. https://doi.org/10.1890/110294

Nones, M., 2015. Implementation of the floods directive in selected EU member states: Implementation of the floods directive. Water Environ. J. 29, 412–418. https://doi.org/10.1111/wej.12129

Nye, M., Tapsell, S., Twigger-Ross, C., 2011. New social directions in UK flood risk management: moving towards flood risk citizenship? J. Flood Risk Manag. 4, 288–297. https://doi.org/10.1111/j.1753-318X.2011.01114.x

O'Donnell, E.C., Lamond, J.E., Thorne, C.R., 2018. Learning and Action Alliance framework to facilitate stakeholder collaboration and social learning in urban flood risk management. Environ. Sci. Policy 80, 1–8. https://doi.org/10.1016/j.envsci.2017.10.013

Oliver, K., 2016. Flooding: a resident's view of Saturday 5th December. Corbridge Matters.

O'Sullivan, J.J., Bradford, R.A., Bonaiuto, M., De Dominicis, S., Rotko, P., Aaltonen, J., Waylen, K., Langan, S.J., 2012. Enhancing flood resilience through improved risk communications. Nat. Hazards Earth Syst. Sci. 12, 2271–2282. https://doi.org/10.5194/nhess-12-2271-2012

Pain, R., 2004. Social geography: participatory research. Prog. Hum. Geogr. 28, 652–663.

Pappenberger, F., Beven, K., Frodsham, K., Romanowicz, R., Matgen, P., 2007a. Grasping the unavoidable subjectivity in calibration of flood inundation models: A vulnerability weighted approach. J. Hydrol. 333, 275–287. https://doi.org/10.1016/j.jhydrol.2006.08.017

Pappenberger, F., Frodsham, K., Beven, K., Romanowicz, R., Matgen, P., 2007b. Fuzzy set approach to calibrating distributed flood inundation models using remote sensing observations. Hydrol Earth Syst Sci 11, 739–752. https://doi.org/10.5194/hess-11-739-2007

Parkes, B.L., Cloke, H.L., Pappenberger, F., Neal, J., Demeritt, D., 2013. Reducing Inconsistencies in Point Observations of Maximum Flood Inundation Level. Earth Interact. 17, 1–27. https://doi.org/10.1175/2012EI000475.1

Partridge, M.D., Rickman, D.S., Olfert, M.R., Tan, Y., 2015. When Spatial Equilibrium Fails: Is Place-Based Policy Second Best? Reg. Stud. 49, 1303–1325. https://doi.org/10.1080/00343404.2013.837999

Paton, D., 2008. Risk communication and natural hazard mitigation: how trust influences its effectiveness. Int. J. Glob. Environ. Issues 8, 2–16. https://doi.org/10.1504/IJGENVI.2008.017256

Paton, D., Johnston, D., 2001. Disasters and communities: vulnerability, resilience and preparedness. Disaster Prev. Manag. Int. J. 10, 270–277. https://doi.org/10.1108/EUM0000000005930

Paton, D., Johnston, D.M., 2006. Disaster Resilience: An Integrated Approach. Charles C Thomas Publisher.

Pereira, Â.G., Rinaudo, J.-D., Jeffrey, P., Blasques, J., Quintana, S.C., Courtois, N., Funtowicz, S., Petit, V., 2003. ICT Tools to Support Public Participation in Water Resources Governance & Planning: Experiences from the Design and Testing of a Multi-Media Platform. J. Environ. Assess. Policy Manag. 05, 395–420. https://doi.org/10.1142/S1464333203001383

Perks, M.T., Russell, A.J., Large, A.R.G., 2016. Technical Note: Advances in flash flood monitoring using unmanned aerial vehicles (UAVs). Hydrol Earth Syst Sci 20, 4005–4015. https://doi.org/10.5194/hess-20-4005-2016

Peters, B.G., 2011. Steering, rowing, drifting, or sinking? Changing patterns of governance. Urban Res. Pract. 4, 5–12. https://doi.org/10.1080/17535069.2011.550493

Peters, B.G., Pierre, J., 1998. Governance Without Government? Rethinking Public Administration. J. Public Adm. Res. Theory 8, 223–243. https://doi.org/10.1093/oxfordjournals.jpart.a024379

Plummer, R., FitzGibbon, J., 2004. Some observations on the terminology in co-operative environmental management. J. Environ. Manage. 70, 63–72. https://doi.org/10.1016/j.jenvman.2003.10.005

Plüss, L., 2014. Steering, Not Rowing? An Analysis of the Political Influence, the Role Perceptions, and the Behavior of Swiss City Councillors in Different Urban Governance Contexts. Urban Aff. Rev. 50, 490–520. https://doi.org/10.1177/1078087413501636

Pomeroy, R.S., Berkes, F., 1997. Two to tango: The role of government in fisheries co-management. Mar. Policy 21, 465–480. https://doi.org/10.1016/S0308-597X(97)00017-1

Rahman, N., Ansary, M.A., Islam, I., 2015. GIS based mapping of vulnerability to earthquake and fire hazard in Dhaka city, Bangladesh. Int. J. Disaster Risk Reduct. 13, 291–300. https://doi.org/10.1016/j.ijdrr.2015.07.003

Reed, M.S., 2008. Stakeholder participation for environmental management: A literature review. Biol. Conserv. 141, 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014

Refsgaard, J.C., Henriksen, H.J., 2004. Modelling guidelines––terminology and guiding principles. Adv. Water Resour. 27, 71–82. https://doi.org/10.1016/j.advwatres.2003.08.006

Renschler, C.S., Wang, Z., 2017. Multi-source data fusion and modeling to assess and communicate complex flood dynamics to support decision-making for downstream areas of dams: The 2011 hurricane irene and schoharie creek floods, NY. Int. J. Appl. Earth Obs. Geoinformation 62, 157–173. https://doi.org/10.1016/j.jag.2017.06.002

Reynard, N.S., Kay, A.L., Anderson, M., Donovan, B., Duckworth, C., 2017. The evolution of climate change guidance for fluvial flood risk management in England. Prog. Phys. Geogr. 41, 222–237. https://doi.org/10.1177/0309133317702566

Risk and Regulation Advisory Council, 2009. Building resilient communities: from idea to sustainable action (No. URN 09/1153). HM Government, London.

Robins, L., Burt, T.P., Bracken, L.J., Boardman, J., Thompson, D.B.A., 2017. Making water policy work in the United Kingdom: A case study of practical approaches to strengthening complex, multi-tiered systems of water governance. Environ. Sci. Policy 71, 41–55. https://doi.org/10.1016/j.envsci.2017.01.008

Robinson, N.A., 2012. Beyond sustainability: environmental management for the Anthropocene Epoch. J. Public Aff. 12, 181–194. https://doi.org/10.1002/pa.1432

Rogers, R.W., 1975. The Protection Motivation Theory of Fear Appeals and Attitude Change. J. Psychol. 91, 93–114.

Rollason, E., Bracken, L.J., Hardy, R.J., Large, A.R.G., 2018. Rethinking flood risk communication. Nat. Hazards 92, 1665–1686. https://doi.org/10.1007/s11069-018-3273-4

Rouillard, J.J., Spray, C.J., 2017. Working across scales in integrated catchment management: lessons learned for adaptive water governance from regional experiences. Reg. Environ. Change 17, 1869–1880. https://doi.org/10.1007/s10113-016-0988-1

Ruiz-Mallén, I., Riboli-Sasco, L., Ribrault, C., Heras, M., Laguna, D., Perié, L., 2016. Citizen Science: Toward Transformative Learning. Sci. Commun. 38, 523–534. https://doi.org/10.1177/1075547016642241

Rykiel, E.J., 1996. Testing ecological models: the meaning of validation. Ecol. Model. 90, 229–244. https://doi.org/10.1016/0304-3800(95)00152-2

Sabatier, P.A., 1986. Top-down and Bottom-up Approaches to Implementation Research: A Critical Analysis and Suggested Synthesis. J. Public Policy 6, 21–48.

Sampson, C.C., Fewtrell, T.J., Duncan, A., Shaad, K., Horritt, M.S., Bates, P.D., 2012. Use of terrestrial laser scanning data to drive decimetric resolution urban inundation models. Adv. Water Resour. 41, 1–17. https://doi.org/10.1016/j.advwatres.2012.02.010

Sampson, C.C., Smith, A.M., Bates, P.D., Neal, J.C., Alfieri, L., Freer, J.E., 2015. A high-resolution global flood hazard model. Water Resour. Res. 51, 7358–7381. https://doi.org/10.1002/2015WR016954

Savage, J.T.S., Bates, P.D., Freer, J.E., Neal, J.C., Aronica, G.T., 2016. When does spatial resolution become spurious in probabilistic flood inundation predictions? Hydrol. Process. 30, 2014–2032. https://doi.org/10.1002/hyp.10749

Schild, R., 2018. Fostering environmental citizenship: the motivations and outcomes of civic recreation. J. Environ. Plan. Manag. 61, 924–949. https://doi.org/10.1080/09640568.2017.1350144

Schnebele, E., Cervone, G., 2013. Improving remote sensing flood assessment using volunteered geographical data. Nat Hazards Earth Syst Sci 13, 669–677. https://doi.org/10.5194/nhess-13-669-2013

Segura-Beltrán, F., Sanchis-Ibor, C., Morales-Hernández, M., González-Sanchis, M., Bussi, G., Ortiz, E., 2016. Using post-flood surveys and geomorphologic mapping to evaluate hydrological and hydraulic models: The flash flood of the Girona River (Spain) in 2007. J. Hydrol. 541, 310–329. https://doi.org/10.1016/j.jhydrol.2016.04.039

Shaw, K., 2012. “Reframing” Resilience: Challenges for Planning Theory and Practice, in: Porter, L., Davoudi, S. (Eds.), Applying the Resilience Perspective to Planning: Critical Thoughts from Theory and Practice. pp. 308–312.

Simonovic, S.P., Ahmad, S., 2005. Computer-based Model for Flood Evacuation Emergency Planning. Nat. Hazards 34, 25–51. https://doi.org/10.1007/s11069-004-0785-x

Skelcher, C., 2000. Changing images of the State: overloaded, hollowed-out, congested. Public Policy Adm. 15, 3–19. https://doi.org/10.1177/095207670001500302

Slovic, P., Kunreuther, H., White, G.F., 1974. Decision processes, rationality and adjustment to natural hazards. Earthscan Publications.

Smith, K.W., 2015. Drone Technology: Benefits, Risks, and Legal Considerations. Seattle J. Environ. Law SJEL 5, [i]-302.

Smith, R.A.E., Bates, P.D., Hayes, C., 2012. Evaluation of a coastal flood inundation model using hard and soft data. Environ. Model. Softw. 30, 35–46. https://doi.org/10.1016/j.envsoft.2011.11.008

Solomon, S., Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change (Eds.), 2007. Climate change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge ; New York.

Sørensen, M.B., Spada, M., Babeyko, A., Wiemer, S., Grünthal, G., 2012. Probabilistic tsunami hazard in the Mediterranean Sea. J. Geophys. Res. Solid Earth 117. https://doi.org/10.1029/2010JB008169

Sousa, D., 2014. Validation in Qualitative Research: General Aspects and Specificities of the Descriptive Phenomenological Method. Qual. Res. Psychol. 11, 211–227. https://doi.org/10.1080/14780887.2013.853855

Spence, A., Pidgeon, N., 2010. Framing and communicating climate change: The effects of distance and outcome frame manipulations. Glob. Environ. Change, 20th Anniversary Special Issue 20, 656–667. https://doi.org/10.1016/j.gloenvcha.2010.07.002

Starkey, E., Parkin, G., 2015. Community Involvement in UK Catchment Management: a review of current knowledge (No. FR/R0021). Foundation for Water Research, Marlow.

Starkey, E., Parkin, G., Birkinshaw, S., Large, A., Quinn, P., Gibson, C., 2017. Demonstrating the value of community-based (‘citizen science’) observations for catchment modelling and characterisation. J. Hydrol. 548, 801–817. https://doi.org/10.1016/j.jhydrol.2017.03.019

Stedman, R.C., 2003. Is It Really Just a Social Construction?: The Contribution of the Physical Environment to Sense of Place. Soc. Nat. Resour. 16, 671–685. https://doi.org/10.1080/08941920309189

Steelman, T.A., McCaffrey, S., 2013. Best practices in risk and crisis communication: Implications for natural hazards management. Nat. Hazards 65, 683–705. https://doi.org/10.1007/s11069-012-0386-z

Steelman, T.A., McCaffrey, S.M., Velez, A.-L.K., Briefel, J.A., 2015. What information do people use, trust, and find useful during a disaster? Evidence from five large wildfires. Nat. Hazards 76, 615–634. https://doi.org/10.1007/s11069-014-1512-x

Steinfuhrer, A., Kuhlicke, C., de Marchi, B., Tapsell, S., Tunstall, S., 2008. Towards flood risk management with the people at risk: from scientific analysis to practice recommendations (and back), in: Samuels, P., Huntingdon, S., Allsop, W., Harrop, J. (Eds.), Flood Risk Management: Research and Practice. CRC Press, Leiden.

Stickler, T., Norbert, S., Greiving, S., Fleischhauer, M., Firus, K., 2012. Planning and Evaluating Participatory Flood Risk Management, in: 12th Congress INTERPRAEVENT. Grenoble.

Strathie, A., Netto, G., Walker, G.H., Pender, G., 2015. How presentation format affects the interpretation of probabilistic flood risk information. J. Flood Risk Manag. https://doi.org/10.1111/jfr3.12152

Stringer, L.C., Reed, M.S., 2007. Land degradation assessment in Southern Africa: integrating local and scientific knowledge bases. Land Degrad. Dev. 18, 99–116. https://doi.org/10.1002/ldr.760

Swanstrom, T., 2008. Regional Resilience: A Critical Examination of the Ecological Framework. Presented at the Urban Affairs Association Annual Meeting, Berkely Institute of Urban and Regional Development, Baltimore MD.

Talen, E., 2000. Bottom-Up GIS: A New Tool for Individual and Group Expression in Participatory Planning. J. Am. Plann. Assoc. 66, 279–294. https://doi.org/10.1080/01944360008976107

Tang, Z., Zhou, Y., Yu, H., Gu, Y., Liu, T., 2017. Developing an Interactive Mobile Volunteered Geographic Information Platform to Integrate Environmental Big Data and Citizen Science in Urban Management, in: Seeing Cities Through Big Data, Springer Geography. Springer, Cham, pp. 65–81. https://doi.org/10.1007/978-3-319-40902-3_4

Teng, J., Jakeman, A.J., Vaze, J., Croke, B.F.W., Dutta, D., Kim, S., 2017. Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. Environ. Model. Softw. 90, 201–216. https://doi.org/10.1016/j.envsoft.2017.01.006

Terpstra, T., 2011. Emotions, Trust, and Perceived Risk: Affective and Cognitive Routes to Flood Preparedness Behavior: Affective and Cognitive Routes to Flood Preparedness Behavior. Risk Anal. 31, 1658–1675. https://doi.org/10.1111/j.1539-6924.2011.01616.x

Terpstra, T., Gutteling, J.M., 2008. Households' Perceived Responsibilities in Flood Risk Management in The Netherlands. Int. J. Water Resour. Dev. 24, 555–565. https://doi.org/10.1080/07900620801923385

Thaler, T., Hartmann, T., 2016. Justice and flood risk management: reflecting on different approaches to distribute and allocate flood risk management in Europe. Nat. Hazards 83, 129–147. https://doi.org/10.1007/s11069-016-2305-1

Thaler, T., Levin-Keitel, M., 2016. Multi-level stakeholder engagement in flood risk management—A question of roles and power: Lessons from England. Environ. Sci. Policy, Participatory and Collaborative Governance for Sustainable Flood Risk Management: An emerging research agenda 55, 292–301. https://doi.org/10.1016/j.envsci.2015.04.007

Thieken, A., Beurton, S., 2012. Key findings of research related to: Flood resilient communities - managing the consequences of flooding (CRUE Synthesis Report No. II–2012), CRUE Flood Risk Management Research Monograph Series. ERA-Net CRUE.

Thieken, A.H., Mariani, S., Longfield, S., Vanneuville, W., 2014. Preface: Flood resilient communities - managing the consequences of flooding. Nat. Hazards Earth Syst. Sci. 14, 33–39. https://doi.org/10.5194/nhess-14-33-2014

Thorne, C.R., Lawson, E.C., Ozawa, C., Hamlin, S.L., Smith, L.A., 2015. Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management: Uncertainties and barriers to adoption of BGI. J. Flood Risk Manag. n/a-n/a. https://doi.org/10.1111/jfr3.12218

Triglav-Cekada, M., Radovan, D., 2013. Using volunteered geographical information to map the November 2012 floods in Slovenia. Nat. Hazards Earth Syst. Sci. 13, 2753–2762. https://doi.org/10.5194/nhess-13-2753-2013

Tritter, J.Q., McCallum, A., 2006. The snakes and ladders of user involvement: Moving beyond Arnstein. Health Policy 76, 156–168. https://doi.org/10.1016/j.healthpol.2005.05.008

Tunstall, S., Johnson, C., Penning-Rowsell, E., 2004. Flood Hazard Management in England and Wales: From Land Drainage to Flood Risk Management, in: Proceedings Of World Congress On Natural Disaster Mitigation. Presented at the World Congress on Natural Disaster Mitigation, Institute of Engineers, New Dehli.

Twigger-Ross, C., Coates, T., Orr, P., Ramsden, M., Stafford, J., 2011. Community Resilience Research: Final Report on Theoretical research and analysis of Case Studies report to the Cabinet Office and Defence Science and Technology Laboratory. Collingwood Environmental Planning Ltd, London.

Twigger-Ross, C., Kashefi, E., Weldon, S., Brooks, K., Deeming, H., Forest, S., Fielding, J., Gomersall, A., Harries, T., McCarthy, S., Orr, P., Parker, D., Tapsell, S., 2014. Flood Resilience Community Pathfinder Evaluation Rapid Evidence Assessment. Defra, London.

UNISDR, 2009. UNISDR terminology on disaster risk reduction. UNISDR, Geneva.

United States Geological Survey, 2016. Flood Inundation Mapping (FIM) Program [WWW Document]. URL https://water.usgs.gov/osw/flood_inundation/ (accessed 4.12.17).

Urwin, K., Jordan, A., 2008. Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. Glob. Environ. Change 18, 180–191. https://doi.org/10.1016/j.gloenvcha.2007.08.002

Usón, T.J., Klonner, C., Höfle, B., 2016. Using participatory geographic approaches for urban flood risk in Santiago de Chile: Insights from a governance analysis. Environ. Sci. Policy 66, 62–72. https://doi.org/10.1016/j.envsci.2016.08.002

Van Alphen, J., Martini, F., Loat, R., Slomp, R., Passchier, R., 2009. Flood risk mapping in Europe, experiences and best practices. J. Flood Risk Manag. 2, 285–292. https://doi.org/10.1111/j.1753-318X.2009.01045.x

Varis, O., Enckell, K., Keskinen, M., 2014. Integrated water resources management: horizontal and vertical explorations and the ‘water in all policies’ approach. Int. J. Water Resour. Dev. 30, 433–444. https://doi.org/10.1080/07900627.2014.912130

Voulvoulis, N., Arpon, K.D., Giakoumis, T., 2017. The EU Water Framework Directive: From great expectations to problems with implementation. Sci. Total Environ. 575, 358–366. https://doi.org/10.1016/j.scitotenv.2016.09.228

Wachinger, G., Renn, O., Begg, C., Kuhlicke, C., 2013. The Risk Perception Paradox-Implications for Governance and Communication of Natural Hazards: The Risk Perception Paradox. Risk Anal. 33, 1049–1065. https://doi.org/10.1111/j.1539-6924.2012.01942.x

Waite, T.D., Chaintarli, K., Beck, C.R., Bone, A., Amlôt, R., Kovats, S., Reacher, M., Armstrong, B., Leonardi, G., Rubin, G.J., Oliver, I., 2017. The English national cohort study of flooding and health: cross-sectional analysis of mental health outcomes at year one. BMC Public Health 17, 129. https://doi.org/10.1186/s12889-016-4000-2

Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A.P., 2004. Resilience, Adaptability and Transformability in Social-ecological Systems. Ecol. Soc. 9. https://doi.org/10.5751/ES-00650-090205

Walker, J., Cooper, M., 2011. Genealogies of resilience: From systems ecology to the political economy of crisis adaptation. Secur. Dialogue 42, 143–160. https://doi.org/10.1177/0967010611399616

Wan, Z., Hong, Y., Khan, S., Gourley, J., Flamig, Z., Kirschbaum, D., Tang, G., 2014. A cloud-based global flood disaster community cyber-infrastructure: Development and demonstration. Environ. Model. Softw. 58, 86–94. https://doi.org/10.1016/j.envsoft.2014.04.007

Warner, J., 2011. Flood planning the politics of water security. I.B. Tauris, London.

Warner, J.F., 2006. More Sustainable Participation? Multi-Stakeholder Platforms for Integrated Catchment Management. Int. J. Water Resour. Dev. 22, 15–35. https://doi.org/10.1080/07900620500404992

Waterton, C., Maberly, S.C., Norton, L.R., Tsouvalis, J., Watson, N.M., Winfield, I.J., 2011. A community approach to catchment management (No. 32), Rural

Economy and Land Use Policy and Practice Note Series. Rural Economy and Land Use Programme, Lancaster.

Watson, N., 2014. IWRM in England: bridging the gap between top-down and bottom-up implementation. Int. J. Water Resour. Dev. 30, 445–459. https://doi.org/10.1080/07900627.2014.899892

Watson, N., Deeming, H., Treffny, R., 2009. Beyond Bureaucracy? Assessing Institutional Change in the Governance of Water in England 2, 13.

Watson, N., Howe, J., 2006. Implementing the EU Water Framework Directive: Experiences of Participatory Planning in the Ribble Basin, North West England. Water Int. 31, 472–487. https://doi.org/10.1080/02508060608691951

Waylen, K.., Holstead, K.., Colley, K., Hopkins, J., 2017. Challenges to enabling and implementing Natural Flood Management in Scotland. J. Flood Risk Manag. 11, S1078–S1089. https://doi.org/10.1111/jfr3.12301

Wehn, U., Rusca, M., Evers, J., Lanfranchi, V., 2015. Participation in flood risk management and the potential of citizen observatories: A governance analysis. Environ. Sci. Policy 48, 225–236.

White, I., O’Hare, P., 2014. From Rhetoric to Reality: Which Resilience, Why Resilience, and Whose Resilience in Spatial Planning? Environ. Plan. C Gov. Policy 32, 934–950. https://doi.org/10.1068/c12117

Whitman, G.P., Pain, R., Milledge, D.G., 2015. Going with the flow? Using participatory action research in physical geography. Prog. Phys. Geogr. https://doi.org/10.1177/0309133315589707

Wiggins, A., He, Y., 2016. Community-based Data Validation in Citizen Science. https://doi.org/10.13016/M2N733

Willis, K.F., Natalier, K., Revie, M., 2011. Understanding Risk, Choice and Amenity in an Urban Area at Risk of Flooding. Hous. Stud. 26, 225–239. https://doi.org/10.1080/02673037.2011.549215

Wing, O.E.J., Bates, P.D., Sampson, C.C., Smith, A.M., Johnson, K.A., Erickson, T.A., 2017. Validation of a 30 m resolution flood hazard model of the conterminous United States. Water Resour. Res. n/a-n/a. https://doi.org/10.1002/2017WR020917

Wood, J., 2005. “How green is my valley?” Desktop geographic information systems as a community-based participatory mapping tool. Area 37, 159–170. https://doi.org/10.1111/j.1475-4762.2005.00618.x

Wood, M., Hostache, R., Neal, J.C., Wagener, T., Giustarini, L., Chini, M., Corato, G., Matgen, P., Bates, P.D., 2016. Calibration of channel depth and friction parameters in the LISFLOOD-FP hydraulic model using medium-resolution SAR data and identifiability techniques. Hydrol Earth Syst Sci 20, 4983–4997. https://doi.org/10.5194/hess-20-4983-2016

Wynne, B., 1996. May the sheep safely graze? A reflexive view of the expert-lay knowledge divide, in: Lash, S., Szerszynski, B., Wynne, B. (Eds.), Risk, Environment and Modernity: Towards a New Ecology, Theory, Culture & Society. Sage Publications, London ; Thousand Oaks, Calif.

Young, O., 2006. Vertical Interplay among Scale-dependent Environmental and Resource Regimes. Ecol. Soc. 11. https://doi.org/10.5751/ES-01519-110127

Zipkin, D.A., Umscheid, C.A., Keating, N.L., Allen, E., Aung, K., Beyth, R., Kaatz, S., Mann, D.M., Sussman, J.B., Korenstein, D., Schardt, C., Nagi, A., Sloane, R., Feldstein, D.A., 2014. Evidence-Based Risk Communication: A Systematic Review. Ann. Intern. Med. 161, 270. https://doi.org/10.7326/M14-0295